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UNC-SAM, A FORTRAN MONTE CARLO SYSTEM  
FOR THE EVALUATION OF NEUTRON OR  
GAMMA-RAY TRANSPORT IN  
THREE-DIMENSIONAL GEOMETRY

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## ABSTRACT

A code system (called UNC-SAM) which evaluates the transport of neutrons or gamma rays using Monte Carlo methods in complex three-dimensional geometry, has been written in FORTRAN for the Control Data Corporation 1604-A computer. The code will calculate fluxes, flux dependent functionals such as doses, and their standard deviations in geometry comprised of rectangular parallelepipeds which, in turn, may contain spheres, cylinders, parallelepipeds, or wedges.

In order to increase the efficiency of the Monte Carlo transport game, UNC-SAM uses an importance sampling technique. In addition, in the particular case of evaluating neutron fluxes in small volume detectors, a scoring by analytical estimation referred to as "flux at a point" is employed.

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## 1. INTRODUCTION

The United Nuclear Corporation Stochastic Approximation Method (UNC-SAM) is a code system in the FORTRAN language for evaluating the transport of neutrons or photons through matter by Monte Carlo techniques. It handles a three-dimensional geometry composed of rectangular parallelepipeds which, in turn, may contain spheres, cylinders, parallelepipeds, or wedges.

UNC-SAM represents the latest result of a continuing effort to develop complex geometry Monte Carlo programs of ever greater versatility and speed.\* Most practical reactor and shield geometries can be handled by the geometry routines. Despite this, the geometry tracking portions of a problem consume considerably less than half the problem running time. In addition to high efficiency geometry routines, region and energy weighting and a special "flux-at-a-point" routine have been incorporated to reduce problem running time when fluxes are required at improbable regions of phase space.

Some applications in which UNC-SAM (or its predecessor ADONIS<sup>1</sup>) have been used successfully are:

1. Transmission of neutrons through ducted shields
2. The analysis of experiments aimed at determining the production of gamma rays in shield materials by high energy neutrons

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\*Most of the numerical techniques employed in UNC-SAM were either formulated or invented by M. H. Kalos who guided the program throughout its development.



3. The transmission of neutrons and gamma rays through air, taking account of air and ground scattering
4. Investigation of shielding provided by proposed reactor containment structure
5. Measurement of shielding effectiveness of nested boxes containing geometrically complex devices
6. Weapon vulnerability studies.

The code system is written in FORTRAN for the Control Data Corporation's (CDC) 1604-A computer. A 32 K core and  $\leq 6$  magnetic tapes are required. UNC-SAM is in reality a chained series of independent programs which process cross-section and geometry data, do the transport problem, and edit the results. A brief summary of the independent programs contained in UNC-SAM follows. Fig. 1 indicates the information flow in the system.

### GENDA

The Generation of Data routine (GENDA) starts with a fundamental set of neutron or photon cross-section data tabulated as a function of energy. It allows for the basic tabulation of the total cross section, the scattering cross section, the Legendre expansion coefficients of the differential scattering cross section, the inelastic scattering cross section for both level and continuum scattering, etc. These data are tabulated generally on differing energy meshes. GENDA processes the data to generate a set of cross-section data on a desired energy mesh. It includes the option of averaging with respect to a given weighting function, prescribed by input, if desired. Otherwise, it determines the desired cross-section set by either linear interpolation or by log-log interpolation. The spectrum of neutrons emitted by inelastic scattering, according to statistical theory, is used for heavier materials. For lighter materials, such as Li and Be, special treatments are available. The output of this routine is a tape which may be used as input to GENPRO.

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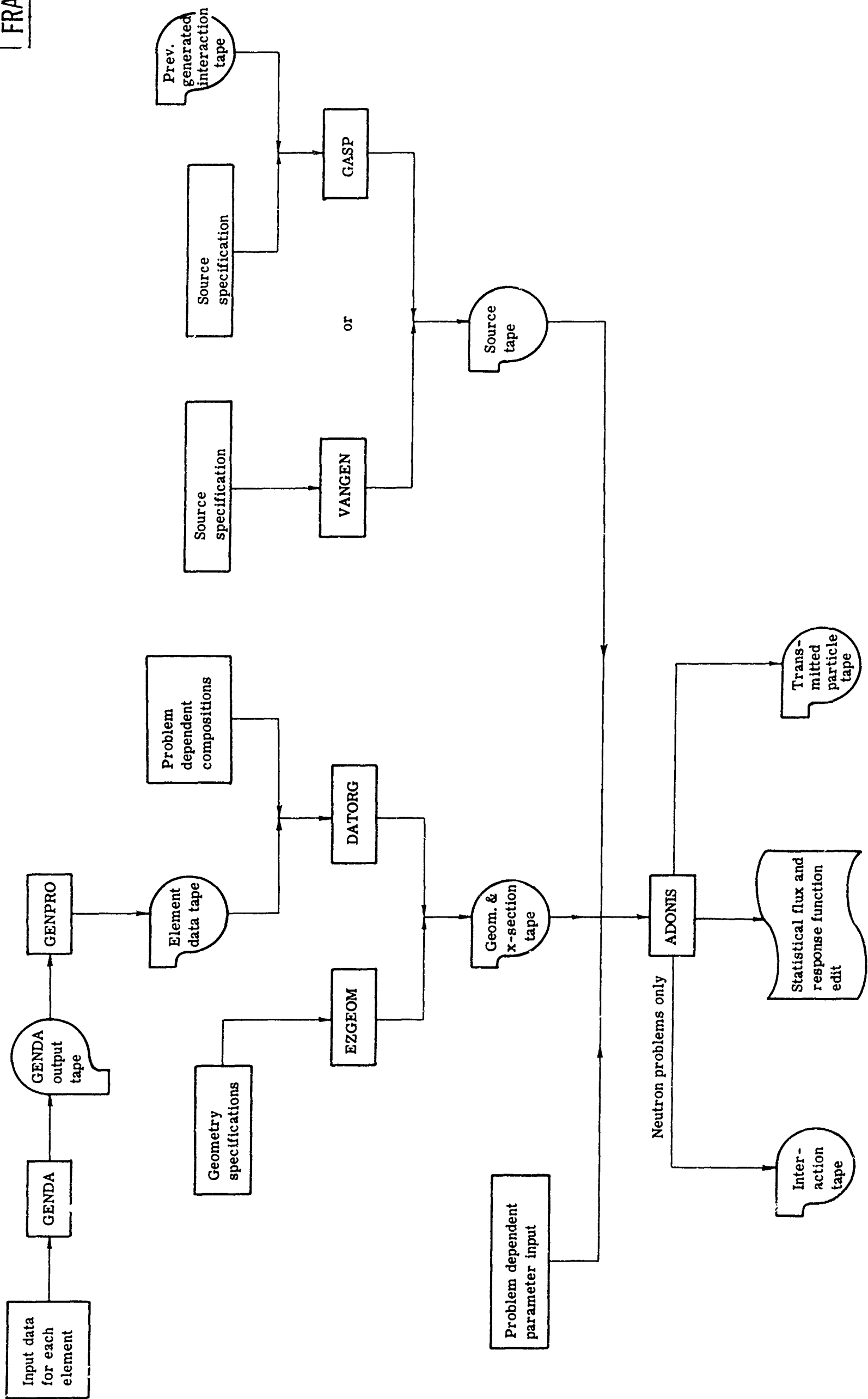


Fig. 1 — Macroscopic flow chart for UNC-SAM

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## GENPRO

The GENDA Processor (GENPRO) routine uses the GENDA output to determine the tables of probabilities peculiar to a nuclide, required for a Monte Carlo code, at a prescribed energy mesh. For instance, the probability that a neutron suffers an elastic scattering is given by the ratio of elastic to total scattering at that energy. The probability of inelastic scattering from one energy to another is computed in this routine. At its conclusion, one has a library tape called the Element Data Tape (EDT), on a given energy mesh to be used in subsequent processing.

Up to this point, no problem oriented input was needed. The functioning of later routines (DATORG, EZGEOM, VANGEN, GASP) will be dependent on such problem oriented data.

## DATORG

Given the concentrations of the materials comprising the configuration, an organized data tape, bearing the total macroscopic cross sections as well as other probabilities for mixtures of nuclides, is created by the DATORG routine. These are the problem-dependent cross-section data tabulated against energy at the prescribed energy mesh previously used in GENDA and GENPRO.

## EZGEOM

This is a routine which takes a simplified geometrical description of the physical system, as provided by the problem originator, and produces the rather complex set of data required by the transport program ADONIS.

The problem originator must decompose space into a set of boxes known as "ordinary regions." Inside these boxes may be placed "nonordinary regions" consisting of spheres, cylinders, wedges, or other boxes. Nonordinary regions may enclose other nonordinary regions.

## VANGEN

Source input corresponding to a primary neutron or gamma-ray problem is provided through the Volume Anisotropic Source Generator (VANGEN). VANGEN creates a source tape with the following types of distributions:

- P-(i) point source
- P-(ii) uniform plane source
- P-(iii) uniform volume source.

Corresponding to each of the above, a choice of angular distributions describing the source is available.

- A-(i) isotropic
- A-(ii) anisotropic according to a given (input) distribution
- A-(iii) monodirectional
- A-(iv) isotropic in the half plane.

Finally, to describe the energy variation of the source, these choices are available:

- E-(i) fission spectrum
- E-(ii) monoenergetic
- E-(iii) an arbitrary distributed energy source with equal probability steps prescribed by input.

The output of VANGEN is a tape for further processing.

## GASP

The routine Gamma Source Particle generator (GASP) computes gamma-ray production from a primary neutron problem to serve as a source for a secondary gamma-ray problem. GASP requires:

1. An interaction tape (generated by a previous ADONIS problem) containing a record of all interactions able to cause gamma-ray emission

2. Probability numbers for each nuclide of the problem giving the probable number of gamma rays emitted as a function of energy
3. An angular distribution (as in VANGEN) for newly created gamma rays.

The routine can cope with the generation of other secondaries upon modification of the interaction tape input. The output of either GASP or VANGEN is a source particle tape which becomes input to ADONIS.

### ADONIS

Given the appropriate output tapes of DATORG, EZGEOM, VANGEN, or GASP, and parametric input defining the problem to be solved, one is now ready to proceed with the neutron or gamma transport code (ADONIS). The program starts sets of 100 initial source particles from the source tape and processes these particles through all of their interactions and migrations, until death, reflection, transmission, or degradation below an energy cutoff occurs. As the particle travels, a variety of information is recorded, including:

1. An interaction tape for future secondary emission processing, or appropriate response function calculations relating to dose calculations, etc.
2. The total flux as a function of energy in each of the ordinary and non-ordinary geometric figures, along with its standard deviation
3. A transmitted particle tape for future processing.

Some of the Monte Carlo techniques employed in the ADONIS code are listed below.

1. Splitting or Russian roulette is performed at each geometric boundary crossed during the process of reaching a collision point. The splitting process is determined by the weights assigned to the regions on either side of the boundary. The weight of any region may vary with the neutron energy. Any additional particles generated by the splitting process are referred to as latent particles.

2. Fluxes in small detector regions are computed by the method referred to as flux-at-a-point. (At present this applies to neutron problems.)

Some of the output provided by ADONIS includes:

1. Number of absorptions, births, deaths, degradations
2. Flux and standard deviation per region energy bin
3. Dose and standard deviation per region.

### SAM

SAM is the main program of an overlay tape containing the DATORG, EZGEOM, VANGEN, GASP and ADONIS programs. SAM functions as a program sequencer reading the title card of each set of input for a given problem calling the program required. It allows a user to place his input deck in any manner providing that, when a program appears in the sequence, all programs that provide input to that program have already been run.

The following sections of this report present a detailed discussion of the individual routines above. Where applicable, the physical principles underlying the program are discussed.



## 2. THE GENERATION OF DATA ROUTINE (GENDA)

Given experimental or theoretical microscopic cross-section data at arbitrary energies in a given range for elements of interest, it is often desirable to process these data into cross-section sets at specified energy point values.

The GENDA routine has been programmed in FORTRAN to accomplish this in the following manner:

1. The raw cross-section data are tabulated according to an established format which can be easily modified and updated. The point values of the input cross-section data are selected to give the best detailed representation of the cross-section variation with energy for the interpolation technique used.
2. For a given element and type of cross section, intermediate point values are obtained from these tables, using either linear or log-log interpolation techniques as directed by the input.
3. Weighted point values of cross sections in a specified energy mesh may be evaluated using a given weighting function. This input function is tabulated in a similar manner as the raw cross-section data and intermediate point values are obtained by interpolation.

## 2.1 TECHNICAL DESCRIPTION

Let  $\sigma(E)$  denote generically a typical cross section at energy  $E$ . This might stand for the total cross section, the scattering cross section, the Legendre expansion coefficient ( $f_p$ ) of the differential scattering cross section, the inelastic scattering cross section for level or continuum scattering, etc. (the cross-section types included appear in the input instructions). Let  $\sigma_0(E)$  be the continuous portion of the typical cross section  $\sigma(E)$ . On occasion, where many resonances exist, a set of resonance parameters  $A_\nu(E_\nu)$  may be given for each generic cross section type such that for the purpose of suitable averages,  $\sigma(E)$  is representable as:

$$\sigma(E) = \sigma_0(E) + \sum_{\nu=1}^{\nu_{\max}} A_\nu(E_\nu) \delta(E-E_\nu) \quad (1)$$

where  $\delta(E-E_\nu)$  is the Dirac delta function of argument  $E-E_\nu$ . This characterization of  $\sigma(E)$  is allowed only when the cross-section averaging routine (CAR) is used; otherwise, an infinitely narrow resonance peak is not physically reasonable, nor computationally manageable.

Let  $E_j^G$ ,  $j = 1, 2, \dots, J$  be a set of final energies in decreasing order at which the output data are to be tabulated. These may be tabulated either as input or computed given the highest energy,  $E_{\max}$ , the number of final energies,  $J$ , and the constant lethargy spacing,  $h$ , such that

$$h = \frac{1}{J} \ln \frac{E_{\max}}{E_J} \quad (2)$$

where  $E_J$  is the lowest energy.

Let  $\phi(E)$  be an arbitrary weighting function supplied by an input table

$$\phi(E) = \phi_0(E) + \sum_{\tau=1}^{\tau_{\max}} B_\tau(E_\tau) \delta(E-E_\tau). \quad (3)$$

(The  $E_\tau$  must not have an energy value equal to any of the  $E_\nu$ .) Let  $\sigma_0(E)$  and  $\phi_0(E)$  be given as functions of energy such that between tabulated values these functions are either linear or exponential.

The GENDA code then provides for the following mutually exclusive options.

1. Find  $\sigma(E_j^G)$ ;  $j = 1, \dots, J_{\max}$  by linear interpolation
2. Find  $\sigma(E_j^G)$ ;  $j = 1, \dots, J_{\max}$  by log-log interpolation
3. Find  $\sigma(E_j^G)$ ;  $j = 2, \dots, J-1$  by

$$\sigma(E_j^G) = \frac{\int_{(E_j^G + E_{j+1}^G)/2}^{(E_j^G + E_{j-1}^G)/2} \sigma_0(E) \phi_0(E) dE + \sum A_\nu(E_\nu) \phi_0(E_\nu) + \sum B_\tau(E_\tau) \sigma_0(E_\tau)}{\int_{(E_j^G + E_{j+1}^G)/2}^{(E_j^G + E_{j-1}^G)/2} \phi_0(E) dE + \sum B_\tau(E_\tau)} \quad (4)$$

where the sums include those values of  $E_\nu$  and  $E_\tau$  falling within the integration interval.

For the purpose of CAR, the energy mesh used is made up of the set of all energies at which  $\sigma$  and  $\phi$  are given, plus the end points of the interval of integration. In the present program, the integration is carried out numerically, using the trapezoidal rule. Consequently, the richer the input mesh, the better the results. It should be noted that exact integration could be performed at the price of some modifications of the program.

The cross section at thermal energy may be included in GENDA. In that case, the lowest entry in the final energy mesh tabulation is the thermal energy.

In addition, GENDA can compute the synthesized differential scattering cross section

$$\sigma(E_j^G, \omega) = \frac{\sigma_n(E_j^G)}{4\pi} \sum_{\ell=0}^L (2\ell+1) f_{\ell}(E_j^G) P_{\ell}(\omega) \quad \text{for } \omega = -1 (0.01) 1 \quad (5)$$

where  $\sigma_n$  = the elastic scattering cross section

$P_{\ell}(\omega)$  = the Legendre polynomial of order  $\ell$  evaluated at the angle cosine  $\omega$

$f_{\ell}(E_j^G)$  = the Legendre expansion coefficient.

All negative values for  $\sigma(E_j^G, \omega)$  are printed out. An edit on the coarser mesh  $-1 (0.1) 1$  is also available.

For the treatment of inelastic scattering, it is necessary to describe in greater detail the kernel  $g(E_j^G, E')$  which represents the probability that, following an inelastic scattering, a neutron at energy  $E_j^G$  will scatter into energy  $E'$ . The spacing of the discrete energy levels in the nucleus is known to decrease with increasing energy. At high energies, the levels are so close that they may be considered as a continuum of energy levels. Let  $E_{BC}$  be the energy at which the discrete level spectrum can be considered to pass over into a continuous spectrum. Then, for incident neutron energies less than or equal to  $E_{BC}$ , only discrete level inelastic scattering occurs. The kernel  $g(E_j^G, E')$  is representable as a sum of delta functions

$$g(E_j^G, E') = g_D(E_j^G, E') = \sum_{\text{all } \nu} a_{\nu}(E_j^G) \delta[E_j^G - (E' + E^{\nu})] \quad E^{\nu} < E_j^G \leq E_{BC} \quad (6)$$

where  $\nu$  = the  $\nu^{\text{th}}$  energy level

$E^{\nu}$  = the energy of the  $\nu^{\text{th}}$  discrete level

$a_{\nu}(E_j^G)$  = the probability that a neutron at energy  $E_j^G$  will scatter into energy

$$E' = E_j^G - E^{\nu}.$$

From the definition of  $g_D$  it follows that

$$\int_0^{E_j^G} g_D(E_j^G, E') dE' = \sum_{\text{all } \nu} a_\nu(E_j^G) = 1 \quad (7)$$

for  $E_j^G \geq E'$ . If  $E_j^G < E'$ , the inelastic scattering cross section is zero and  $g_D(E_j^G, E')$  is undefined.

If the incident neutron energy is greater than  $E_{BC}$ , two cases must be considered.

1. If  $E_j^G$  is sufficiently large that the probability of discrete level scattering is zero, then only continuum level scattering occurs. Let  $E_{BD}$  be the energy above which all  $a_\nu$  are zero, then the kernel  $g(E_j^G, E')$  can be represented by a continuous probability distribution function,  $g_c(E_j^G, E')$  which satisfies the following condition.

$$\int_0^{E_j^G} g_c(E_j^G, E') dE' = 1 \quad (8)$$

2. If  $E_{BC} < E_j^G \leq E_{BD}$ , then both continuum and discrete level scattering occur. Both the continuum and discrete kernels,  $g_0$  and  $a_\nu$ 's are computed, satisfying the normalization given by Eqs. 7 and 8. Hence, the inelastic scattering kernel is

$$g(E_j^G, E) = \frac{\sigma_{nn',c}(E_j^G) g_c(E_j^G, E') + \sigma_{nn',D}(E_j^G) g_D(E_j^G, E')}{\sigma_{nn',c}(E_j^G) + \sigma_{nn',D}(E_j^G)} \quad (9)$$

where  $\sigma_{nn',c}$  and  $\sigma_{nn',D}$  are the cross sections for the excitation of the continuum and of the discrete levels, respectively.

The continuum energy spectrum of neutrons emitted per inelastic scattering at energy  $E$  is obtained using a routine called ASPIC which computes the probability  $g(E, E')$  according to a statistical theory.\*

$$g^{(i)}(E, E') = \frac{E' \sigma_c^{(i)}(E') \rho^{(i)}(E-E')}{\int_0^E E' \sigma_c^{(i)}(E') \rho^{(i)}(E-E') dE'} \quad (10)$$

where  $\sigma_c^{(i)}(E)$  is the cross section for compound nucleus formation and  $\rho^{(i)}(E)$  is the level density in the nucleus  $i$  ( $i=1$  refers to the target nucleus).

The following form is assumed for the level density:

$$\begin{aligned} \rho^{(i)}(E) &= 0 & \text{for } E < E_1^{(i)} \\ \rho^{(i)}(E) &= \rho_0 & \text{for } E_1^{(i)} < E < E_0^{(i)} \\ \rho^{(i)}(E) &= \rho_0 \exp [2\sqrt{a^{(i)}E} - 2\sqrt{a^{(i)}E_0^{(i)}}] & \text{for } E > E_0^{(i)}. \end{aligned} \quad (11)$$

For the treatment of  $(n, 2n)$  reactions, it is assumed that the first neutron has the distribution (Eq. 10) where  $i = 1$ . After the emission of the first neutron, the target nucleus is left at excited states  $E^+$  with a population density:

$$R(E, E^+) = g^{(i)}(E, E-E^+). \quad (12)$$

$R(E^+)$  has a maximum at  $E^+ = E - \sqrt{E/a^{(1)}}$  [ $\sqrt{E/a^{(1)}}$  is the nuclear temperature].

We make the simplifying assumption that all secondary neutrons are emitted from the states  $E^+ = E - \sqrt{E/a^{(1)}}$ . Applying statistical theory, the spectrum of secondary neutrons per  $(n, 2n)$  collision is given by

$$g^{(2)}[E - \sqrt{E/a^{(1)}} - E_t, E'] \quad (13)$$

---

\*See terminology and definitions at the end of this section.

where  $E_t$  is the threshold for the  $(n,2n)$  reaction,  $g^{(2)}$  is given by Eq. 10, and the superscript (2) refers to the nucleus left after the  $(n,2n)$  reaction on the target.

In order to account for the neutrons leading to the ground state of this final nucleus, one should set  $E_t^{(2)} \approx 0$  [choose  $E_t^{(2)} = 0.01$ ]. Hence, the composite spectrum of neutrons emitted per  $(nn'; n,2n)$  reaction is given by

$$g(E, E') = g^{(1)}(E, E') + \frac{\sigma_{n,2n}(E)}{\sigma_{nn',c}(E)} g^{(2)}(E, E') \quad (14)$$

where  $\sigma_{n,2n}(E)$  is included into  $\sigma_{nn',c}(E)$  in GENDA.

In the event that the core storage requires more than 18,000 words for  $g(E, E')$ , the code determines a lowest value for  $E'$  (which will be higher than the lowest energy of the problem) so that  $g(E, E')$  fits in storage. The portion of  $g(E, E')$  neglected is generally negligible.

The above description of the calculation of the probability  $g(E, E')$  is not adequate for light nuclei. Special treatments for lithium and beryllium are available at the user's option.

The GENDA Li option<sup>2</sup> (see Fig. 2) assumes a continuous spectrum for  $E_j^G \geq 3.95$  Mev. For  $E$  below 3.95 Mev, the inelastic scattering arises only from the excitation of the 0.477-Mev level.

The continuous probability distribution function,  $g_c(E, E')$ , is taken as constant with a value of  $1/E_{\max}$  where

$$E_{\max} = 1.040 E_j^G - 4.100 \quad (15)$$

and stretches from  $E' = 2 \times 10^{-6}$  Mev to an  $E_j'$  such that  $E_{j+1}' \geq E_{\max} \geq E_j'$  where  $E_j'$  and  $E_{j+1}'$  are adjacent energies in the integration mesh. It should

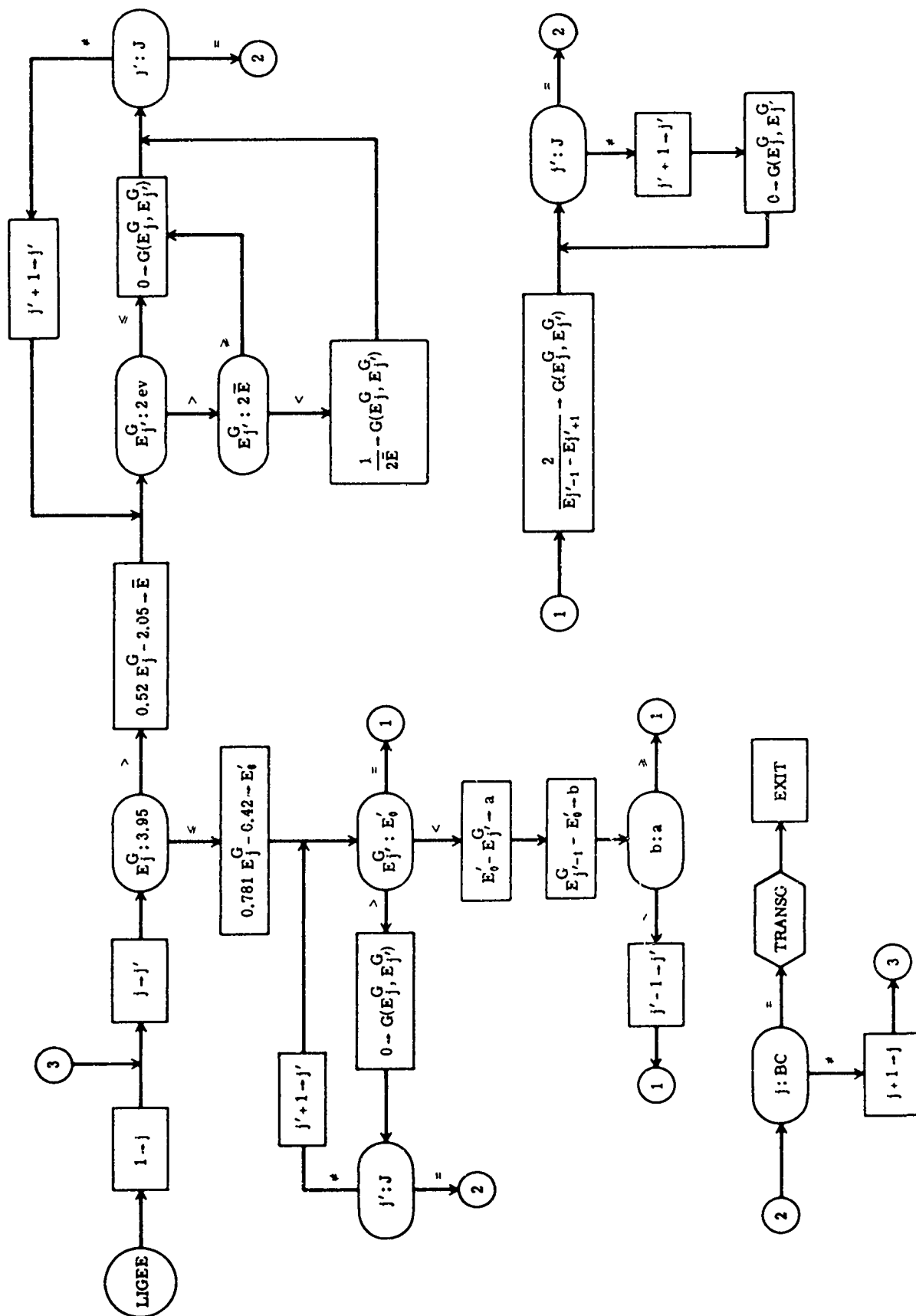


Fig. 2 -- Lithium  $g(E, E')$  computation



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be noted that

$$\int g_c(E, E') dE' = \frac{E'_{j+1} + E'_j}{2 E_{\max}} \quad (16)$$

is not equal to 1, though close to it. Because of the Li nucleus recoil,  $g_D(E, E')$  is obtained as follows:

$$g_D(E, E') = \frac{2 \delta(E' - E'_j)}{E'_{j+1} - E'_{j-1}} \quad (17)$$

where for each  $E$  the value of  $E'_j$  is selected which lies closest to

$$E'_0 = 0.781 E - 0.420 \text{ Mev} \quad (18)$$

The GENDA Be option<sup>3</sup> (see Fig. 3) uses revised data as obtained by Goldstein and Mechanic.<sup>4</sup>

Briefly,

1. For  $E_j^G < 2 \text{ Mev}$ :

$$g(E_j^G, E') = 0$$

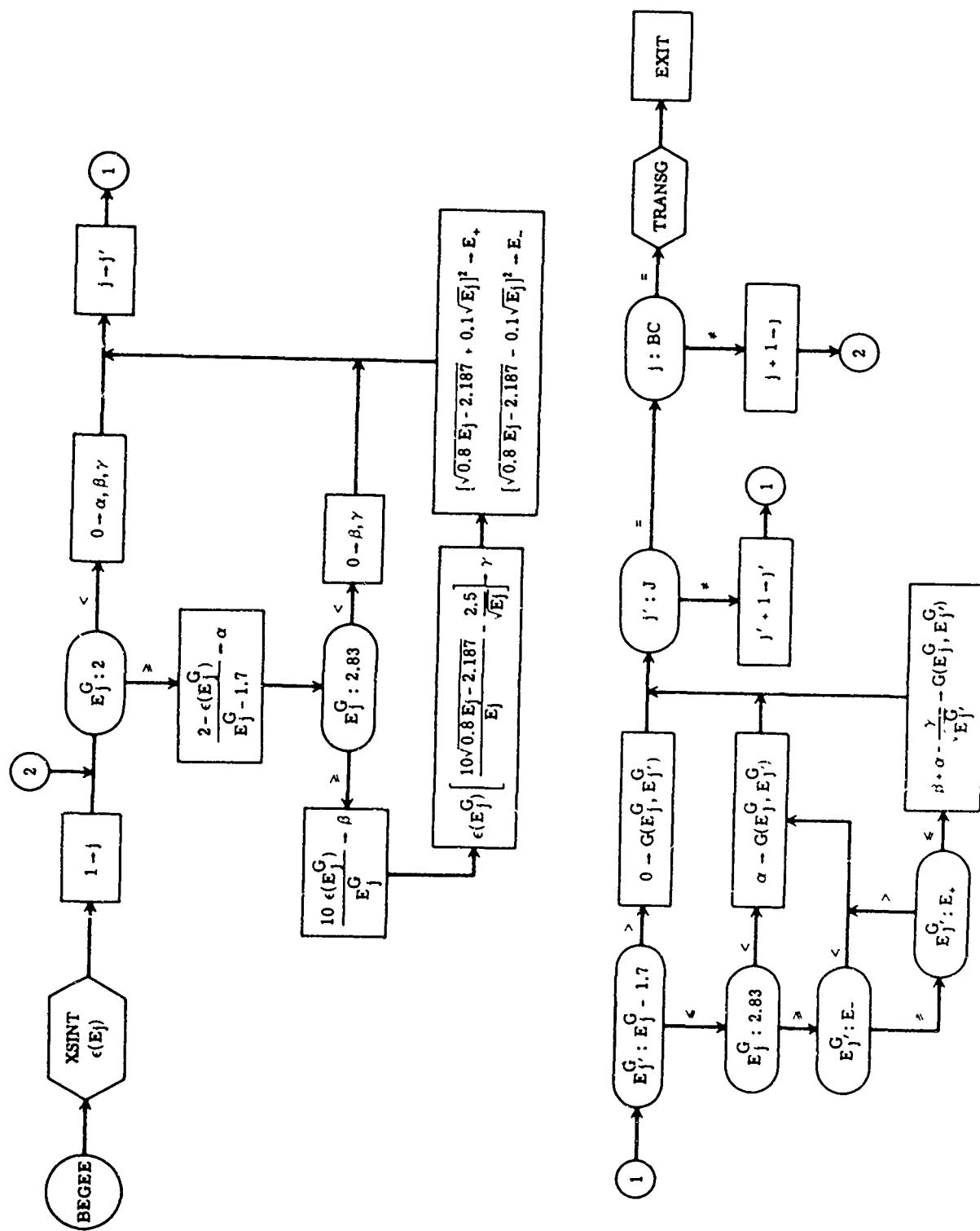
2. For  $2 \text{ Mev} \leq E_j^G \leq 2.83 \text{ Mev}$ :

Of the two types of neutrons emitted,  $\epsilon(E_j^G)$  go via excitation of the 2.43-Mev level of  $\text{Be}^9$ . The remaining  $2 - \epsilon$  neutrons are emitted with a constant distribution stretching from zero to the highest energy allowed (namely  $E - 1.7$ ).

$$g_c(E_j^G, E') = \frac{2 - \epsilon(E_j^G)}{E_j^G - 1.7} \quad (19)$$

3. For  $E_j^G \geq 2.83 \text{ Mev}$ :

The contribution from the discrete level must be added. Thus, the overall distribution  $g(E_j^G, E')$  becomes

Fig. 3 - Beryllium  $g(E, E')$  computation

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$$g(E_j^G, E') = g_c(E_j^G, E') + \epsilon(E_j^G) \left[ \frac{10}{E_j^G} - \frac{1}{\sqrt{E'}} \left( \frac{10\sqrt{0.8 E_j^G - 2.187}}{E_j^G} - \frac{2.5}{\sqrt{E'}} \right) \right]$$

(20)

$\epsilon(E_j^G)$  is taken from the data compiled by Lustig and Kalos.<sup>5</sup>

### Terminology for Section 2.1

$E_t$	the threshold of the (n,2n) reaction
$a^{(1)}, E_0^{(1)}$	level density parameters for the target nucleus
$a^{(2)}, E_0^{(2)}$	level density parameters for the nucleus
$E_1^{(1)}$	energy at which the continuum starts
$E_1^{(2)}$	should be set equal to 0.01
$\sigma_c^{(1)}$	cross section for compound nucleus formation of the target nucleus
$\sigma_c^{(2)}$	cross section for compound nucleus left over after the (n,2n) reaction.

## 2.2 THE PREPARATION OF INPUT DATA FOR GENDA

Unless otherwise stated, all data for this code are in standard FORTRAN E format. The data are punched in six fields of 10 columns each (i.e., 6E10.4). For the general data decks, it is in the order of energy followed by its cross section.

### Example

#### Column

1-10	$E_1$
11-20	$\sigma(E_1)$
21-30	$E_2$
31-40	$\sigma(E_2)$
41-50	$E_3$
51-60	$\sigma(E_3)$

10	20	30	40	50	60
$E_1$	$\sigma(E_1)$	$E_2$	$\sigma(E_2)$	$E_3$	$\sigma(E_3)$

All energies must span the range from  $E_{\max}$  to  $E_{J\max}^G$  (the minimum energy) with the exception of the discrete inelastic scattering cross section ( $\sigma_{nn',L}$ ).

The data control information is in integer format, with the exception of the true mass number which is in F format.

## 2.3 GENDA PROBLEM INPUT

### 2.3.1 Title Card

Any 80 Hollerith characters (e.g., user's name, element name, date, etc.)

### 2.3.2 Problem Control Card

Column	Item
1-3	Number of elements (NEL)
4-7	Number of final energies (JMAX) ( $\leq 450$ )
8	IEN = 0 – compute final energy table with fixed lethargy IEN = 1 – final energy table is input
9	IPHI = 0 – weighting function $\phi_c(E)$ is not present IPHI = 1 – weighting function $\phi_c(E)$ is present
10	IDELP = 0 – table of $B_T(E_T)$ is not present IDELP = 1 – table of $B_T(E_T)$ is present

#### Note:

IDELP must = 0 if IPHI = 0.

### 2.3.3 Energy Input

For IEN = 0

Column	Item	
1-10	$E_{MAX}$ - maximum energy (Mev)	Floating
11-20	H, fixed lethargy step	Floating
	$\frac{1}{JMAX} \ln \frac{E_{MAX}}{E_{JMAX}}$	

For IEN = 1

Energy table  $E_j^G$ ,  $j = 1, 2, \dots, JMAX$ ;  $E_j^G > E_{j+1}^G$

Format (6E10.4)

### 2.3.4 Weighting Function $\phi_c(E)$ (IPHI = 1)

#### Identification Card

Column	Item
1-6	Any six Hollerith characters for identification
8	= 1 - linear
	= 2 - linear on log-log paper
9-12	Number of $\phi_c(E)$ tabulated ( $\leq 300$ )

#### $E^\phi$ , $\phi_c(E^\phi)$ Data Deck

##### Note:

The  $\phi_c(E^\phi)$  must be included if CAR type group averaging is to be used.

### 2.3.5 Weighting Function $B_T(E_T)$ (IPHI = 1 and IDELP = 1)

#### Identification Card

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $B_T$ tabulated ( $\leq 99$ entries)

#### $E_T$ , $B_T(E_T)$ Data Deck

## 2.4 GENDA ELEMENT INPUT

### 2.4.1 Element Control Card

Column	Item
1-6	Element name, Hollerith format
7-13	True mass (F format)
14-23	Integral mass (numerical identification) integer.
DDDDZZZEEE	D - field for data
14	Z - field for atomic number
23	E - field for element identification
	E = 000 if natural element
24-50	Control for the following
	Data = 1 - data are present
	Data = 0 - data are not present
24	Blank
25	Total cross section, $\sigma_T$
26	Elastic scattering cross section, $\sigma_n$
27, 28	The order of expansion ( $T^N \leq 20$ , $f_p$ , $p = 1, 2, \dots, T^N$ ) if the elastic scattering is anisotropic
29	Excitation of discrete levels, $\sigma_{nn',L}$
30, 31	The order of expansion ( $T^L$ ) if the excitation of discrete levels is anisotropic
32	Excitation of the continuum, $\sigma_{nn',c}$ (includes $\sigma_{n,2n}$ )
33,34	The order of expansion ( $T^c$ ) if the excitation of the continuum is anisotropic
35	Cross section for the emission of two neutrons $\sigma_{n,2n}$
36	Fission cross section, $\sigma_f$
37	Absorption cross section, $\sigma_{a,\alpha\beta}$
38	Transport cross section, $\sigma_{tr}$
39	Cross section for the emission of an $\alpha$ particle $\sigma_\alpha$
40	Cross section for the emission of a proton, $\sigma_p$
41	Cross section for the emission of $H_2$ , $\sigma_{H_2}$
42	Cross section for the emission of $H_3$ , $\sigma_{H_3}$
43	Radiative capture cross section, $\sigma_{n,\gamma}$
44	Fission $\gamma$ spectra
45	Absorption $\gamma$ spectra
46	Nonelastic $\gamma$ spectra
47	$\nu(E)$ data
48	$\eta(E)$ data
49	Edit synthesized $f_p$ data
50	Thermal data



### 2.4.2 Total Cross Section, $\sigma_T$

#### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 – linear = 2 – linear on log-log paper
10	= 0 – $\sigma(E_j^G)$ found by interpolation = 1 – $\sigma(E_j^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 – no resonance parameters = 1 – resonance parameters, $A_\nu$ for $\sigma_T$

#### $E, \sigma_T(E)$ Data Deck

#### Thermal Value of $\sigma_T$ (Format E10.4)

#### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

#### $E_\nu, A_\nu(E_\nu)$ Data Deck

### 2.4.3 Elastic Scattering Cross Section, $\sigma_n$

#### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 – linear = 2 – linear on log-log paper
10	= 0 – $\sigma(E_j^G)$ found by interpolation = 1 – $\sigma(E_j^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 – no resonance parameters = 1 – resonance parameters, $A_\nu$ for $\sigma_n$

### E, $\sigma_n(E)$ Data Deck

#### Thermal Value for $\sigma_n$ (Format E10.4)

#### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

### $E_\nu, A_\nu(E_\nu)$ Data Deck

#### 2.4.4 Angular Distribution Data, $f_p$

Anisotropic elastic scattering for each  $f_p$ ,  $p = 1, 2, \dots, T^N$  ( $T^N \leq 20$ ).

#### Identification Card (one for each $f_p$ data deck)

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear = 2 - linear on log-log paper
10	= 0 - $f_p(E_G)$ found by interpolation = 1 - $f_p(E_G)$ found by CAR type averaging
11-14	Number of $f_p(E)$ tabulated ( $\leq 1100$ )

#### 2.4.5 Inelastic Scattering Data, Discrete, $\sigma_{nn',L}$

#### Inelastic Scattering Data, Discrete, Control Card

Column	Item
1-10	$E_{BD}$ , energy at which the discrete spectrum begins. This value can be less than $E_{MAX}$ (e.g., $E_{MAX} = 18.01739$ Mev, $E_{BD} = 7.93$ Mev)
11-13	NU, number of level parameter $\cdot a_\nu \sigma_{nn',L}$ ( $\leq 20$ )

## Excitations of Discrete Levels, $\sigma_{nn',L}$

### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear = 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation = 1 - $\sigma(E_j^G)$ found by CAR type averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 - no resonance parameters = 1 - resonance parameters, $A_\nu$ , for $\sigma_{nn',L}$

$E, \sigma_{nn',L}(E)$  Data Deck from  $E_{BD}$  to  $E_j^G \text{ MAX}$

Thermal Value of  $\sigma_{nn',L}$  (Format E10.4)

### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

$E_\nu, A_\nu(E_\nu)$  Data Deck

### $E_\nu$ Deck

$\nu = 1, 2, \dots, NU$        $E_1 < E_2 < \dots < E_{NU}$  (format 6E10.4)

### Level Parameters $a_\nu \sigma_{nn',L}$

Identification Card (one for each deck of  $A_\nu \sigma_{nn',L}$ , as  $\nu = 1, 2, \dots, NU$ )

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear = 2 - linear on log-log paper

Column	Item
10	$= 0 - a_{\nu}\sigma_{nn',L}(E_j^G)$ found by interpolation $= 1 - a_{\nu}\sigma_{nn',L}(E_j^G)$ found by CAR type averaging
11-14	Number of $a_{\nu}\sigma_{nn',L}$ tabulated ( $\leq 1100$ )

$E, a_{\nu}\sigma_{nn',L}(E)$  Data Deck from  $E_{BD}$  to  $E_j^G \text{ MAX}$

Thermal Value of  $a_{\nu}\sigma_{nn',L}$  (Format E10.4)

Identification Card for  $A_{\nu}$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_{\nu}$ tabulated ( $\leq 99$ )

$E_{\nu}, A_{\nu}(E_{\nu})$  Data Deck

Anisotropic  $\sigma_{nn',L}$

The routines to handle this cross section have not been programmed.

2.4.6 Excitation of the Continuum,  $\sigma_{nn',c}$  (Includes  $\sigma_{n,2n}$ )

Inelastic Scattering Data, Continuous, Control Card

Column	Item
1-10	$E_{BC}$
13	IGOP: Option to commute $G(E, E')$ IGOP = 1 - ASPIC IGOP = 2 - lithium special code IGOP = 3 - beryllium special code

## Excitation of the Continuum, $\sigma_{nn',c}$

### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 – linear = 2 – linear on log-log paper
10	= 0 – $\sigma(E_j^G)$ found by interpolation = 1 – $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 – no resonance parameters = 1 – resonance parameters, $A_\nu$ for $\sigma_{nn',c}$

$E, \sigma_{nn',c}(E)$  Data Deck ( $E_{MAX} = E_{MIN}$ )

Thermal Value of  $\sigma_{nn',c}$  (Format E10.4)

### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

$E_\nu, A_\nu(E_\nu)$  Data Deck

IGOP = 1

### Parameters for the Temperature Model of the Nucleus

Column	Item
1-10	$E_t$ , the threshold energy of the (n,2n) reaction
11-20	$a^{(1)}$ – level density parameter for the target nucleus
21-30	$a^{(2)}$ – level density parameter for the nucleus after an (n,2n) reaction
31-40	$E_0^{(1)}$ – level density parameter for the target nucleus
41-50	$E_0^{(2)}$ – level density parameter for the nucleus after an (n,2n) reaction
51-60	$E_1^{(1)}$ – first excited state
61-70	$E_1^{(2)}$ – should be set equal to 0.0

# Cross Section for the Emission of Two Neutrons, $\sigma_{n,2n}$

## 1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_i^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 - no resonance parameters
	= 1 - resonance parameters, $A_\nu$ for $\sigma_{n,2n}$

## 2. $E, \sigma_{n,2n}(E)$ Data Deck

## 3. Thermal Value of $\sigma_{n,2n}$ (Format E10.4)

## 4. Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

## 5. $E_\nu, A_\nu(E_\nu)$ Data Deck

# Cross Section for Compound Nucleus Formation of the Target Nucleus, $\sigma_c^{(1)}$

## 1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear
	= 2 - linear on log-log paper
10	= 0 - $\sigma(E_i^G)$ found by interpolation
	= 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )

## 2. $E, \sigma_c^{(1)}(E)$ Data Deck

## Cross Section for Compound Nucleus Left Over After the (n,2n) Reaction, $\sigma_c^{(2)}$

### 1. Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 – linear = 2 – linear on log-log paper
10	= 0 – $\sigma(E_j^G)$ found by interpolation = 1 – $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )

### 2. E, $\sigma_c^{(2)}(E)$ Data Deck

IGOP = 2 ( Lithium Special Code)

No input required.

IGOP = 3 (Beryllium Special Code)

### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 – linear = 2 – linear on log-log paper
10	= 0 – $\epsilon(E_j^G)$ found by interpolation = 1 – $\epsilon(E_j^G)$ found by CAR type group averaging
11-14	Number of $\epsilon(E)$ tabulated ( $\leq 1100$ )

E,  $\epsilon(E)$  Data Deck

Anisotropic  $\sigma_{nn',c}$

The routines to handle this cross section have not been programmed.

#### 2.4.7 Cross Section for the Emission of Two Neutrons, $\sigma_{n,2n}$

(If  $\sigma_{n,2n}$  has been supplied for the ASPIC routine do not input again and do not flag  $\sigma_{n,2n}$  on the element control card.)

##### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear = 2 - linear on log-log paper
10	= 0 - $\sigma(E_j^G)$ found by interpolation = 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 - no resonance parameters = 1 - resonance parameters, $A_\nu$ for $\sigma_{n,2n}$

##### $E, \sigma_{n,2n}(E)$ Data Deck

##### Thermal Value of $\sigma_{n,2n}$ (Format E10.4)

##### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

##### $E_\nu, A_\nu(E_\nu)$ Data Deck

For the following eight cross sections (see Section 2.4.8) the following general format is to be used in the order of the cross sections listed.

##### Identification Card

Column	Item
1-6	Any six Hollerith characters
7	= 1 - linear = 2 - linear on log-log paper



10	= 0 - $\sigma(E_j^G)$ found by interpolation = 1 - $\sigma(E_j^G)$ found by CAR type group averaging
11-14	Number of $\sigma(E)$ tabulated ( $\leq 1100$ )
15	= 0 - no resonance parameters = 1 - resonance parameters, $A_\nu$ for $\sigma$

### E, $\sigma(E)$ Data Deck

### Thermal Value of $\sigma$ (Format E10.4)

### Identification Card for $A_\nu$

Column	Item
1-6	Any six Hollerith characters
7-8	Number of $A_\nu$ tabulated ( $\leq 99$ )

### $E_\nu$ , $A_\nu(E_\nu)$ Data Deck

### 2.4.8 Other Cross Sections

1. Fission Cross Section,  $\sigma_f$
2. Absorption Cross Section,  $\sigma_{abs}$
3. Transport Cross Section,  $\sigma_{tr}$
4. Cross Section for the Emission of an  $\alpha$  Particle,  $\sigma_\alpha$
5. Cross Section for the Emission of a Proton,  $\sigma_p$
6. Cross Section for the Emission of  $H_2$ ,  $\sigma_{H_2}$
7. Cross Section for the Emission of  $H_3$ ,  $\sigma_{H_3}$
8. Radiative Capture Cross Section,  $\sigma_{n,\gamma}$

The routines to handle fission  $\gamma$  spectra, absorption  $\gamma$  spectra, nonelastic  $\gamma$  spectra,  $\nu(E)$  data, and  $\eta(E)$  data have not been programmed.

If the program control card specifies more than one element, repeat Section 2.4 of the above input preparation for each element.

## 2.5 GENDA OUTPUT

The GENDA output consists of two edits. The first edit tabulates the input data in the same order as they appear in the input cards. The second edit tabulates the cross-section data at the output mesh energies, as described in Section 2.1, and arranges them in an easily readable manner.

### 3. THE GENERATION DATA ROUTINE PROCESSOR (GENPRO)

The cross-section data generated by GENDA may be used in various ways. However, in Monte Carlo type calculations, what has to be determined once a collision occurs, is

1. The type of event which takes place
2. The energy and direction angle of the emerging particle, if any.

The GENPRO program processes the GENDA output to tabulate probabilities peculiar to a nuclide at a prescribed energy mesh as follows.

1. It computes the probability of elastic scattering, inelastic scattering, and absorption.
2. In case of anisotropic elastic scattering, it tabulates the cosines of angles between which scattering is equi-probable.
3. In case of inelastic scattering, two possibilities exist.
  - a. If the spectrum has a continuous part, it computes energies to which the particle scatters with equal probability.
  - b. If the spectrum is representable by  $\nu$  distinct levels, it tabulates the probability that the particle will scatter to the level  $E_\nu$ .

It is important to note at this point that the maximum number of output energies is different for GENDA, GENPRO, and the subsequent Monte Carlo programs. Indeed, because of the need of fine tabulation of particular cross sections, GENDA

was expanded to handle 450 output energy points. On the other hand, GENPRO can only handle 401 energy points due to core storage limitations. The UNC Monte Carlo programs are further restricted to a maximum energy mesh of 81 points. Therefore, in any Monte Carlo type calculations, input to GENDA must be consistent with the above restrictions.

Also, the output energy mesh for GENDA is variable. However, if it is used in connection with GENPRO, a fixed lethargy interval must be used.

### 3.1 TECHNICAL DESCRIPTION

The cross-section data for each element provided by GENDA are written on a magnetic tape called the Genda Output Tape (GOT).

GENPRO uses GOT to create an Element Data Tape (EDT) which contains the following information:

1. The number of energy points, J
2. The set of final energies in increasing order  $E_j^G$  (using the given constant lethargy step).

Then, for each element,

1. The total cross section at each final energy,  $\sigma_T(E_j^G)$ , is transmitted to the EDT
2. The probabilities of elastic and inelastic scattering and absorption are computed.

$$P_S(E_j^G) = \frac{\sigma_S(E_j^G)}{\sigma_T(E_j^G)} \quad (21)$$

$$P_{nn'}(E_j^G) = \frac{\sigma_{nn'}(E_j^G)}{\sigma_T(E_j^G)} \quad (22)$$

$$P_A(E_j^G) = 1 - P_S(E_j^G) - P_{nn'}(E_j^G) \quad (23)$$

$P_S$  and  $P_A$  tables are then transmitted to the EDT.

It should be noted that for neutron absorption,  $P_A$  contains both fission and capture probabilities.

3. In the event of elastic scattering, the following calculation is performed to decide whether or not the scattering is isotropic.

The angular distribution data supplied by GOT in the form of Legendre expansion coefficients  $f_\ell$ 's is tested for each energy point. Let

$$\sigma(\omega=1) = \sum_{\ell=0}^L (2\ell + 1) f_\ell(E_j^G) \quad (24)$$

$$\sigma(\omega=-1) = \sum_{\ell=0}^L (2\ell + 1) f_\ell(E_j^G) (-1)^\ell \quad (25)$$

$$\sigma(\omega=0) = \sum_{\text{even } \ell \text{'s}} (2\ell + 1) f_\ell(E_j^G) P_\ell(0) \quad (26)$$

where the notation used is given in the GENDA section.

The largest and smallest of these are selected and referred to as  $M$  and  $m$ , respectively.

Then if

$$\frac{M - m}{0.5(M+m)} \leq 0.05, \quad (27)$$

the angular distribution is taken as isotropic and no further tabulated data are required. (See Section 7.)

Otherwise, the scattering is treated as anisotropic and GENPRO proceeds to compute the angles  $\theta$  through which it is equally probable to scatter.

Since the differential scattering cross section is given by

$$\sigma(E_j^G, \mu) = \frac{\sigma_n(E_j^G)}{4\pi} \sum_{\ell=0}^L (2\ell+1) f_{\ell}(E_j^G) P_{\ell}(\mu) \quad (28)$$

where  $\mu = \cos \theta$  varies from  $-1$  to  $+1$ , GENPRO computes

$$F(\mu, E_j^G) = \frac{2\pi}{\sigma_n(E_j^G)} \int_{-1}^{\mu} \sigma(E_j^G, \mu) d\mu \quad (29)$$

which gives the  $\mu$  probability distribution. The integration of Eq. 28 yields

$$F(\mu, E_j^G) = \sum_{\ell=0}^L \frac{1}{2} f_{\ell}(E_j^G) [P_{\ell+1}(\mu) - P_{\ell-1}(\mu)] \quad (30)$$

with the convention that  $P_{-1} = -1$ .

$F(\mu, E_j^G)$  is computed for  $-1 \leq \mu \leq +1$  in steps of 0.01. Then GENPRO locates  $\mu_n$  such that

$$F(\mu_n) = \frac{n}{N} \text{ for } n = 0, 1, 2, \dots, N \quad (31)$$

$N$  is usually 10 for the Monte Carlo programs.

For statistical considerations, it is desirable to use a new variable  $\chi$  which is related to  $\mu$  by

$$\mu = \cos \theta = 1 - 2\chi \quad (32)$$

where now  $\chi$  varies from 0 to 1.

Hence,

$$\chi_n = \frac{1 - \mu_n}{2}, \quad n = 0, 1, 2 \dots N \quad (33)$$

is tabulated and transmitted to the EDT as Table CHI.

4. In the event of continuum inelastic scattering (which is determined by the threshold energy supplied by GOT), the probability that a neutron entering collision at energy  $E_j^G$  will emerge from an inelastic scattering collision at energy  $E'$  has been computed by GENDA and entered into GOT in the form of  $g_c(E_j^G, E')$  with  $E_j^G > E_{BD}$ .

To obtain the energies to which it is equally probable to scatter, GENPRO calculates

$$G(E_j^G, E) = \int_0^E g_c(E_j^G, E') dE', \quad E \leq E_j^G \quad (34)$$

where the integral is evaluated by the trapezoidal rule.

Note that if one considers the spectrum of neutrons emitted by  $(nn')$  reactions, the integral (Eq. 34) is normalized to 1.

Indeed,

$$G(E_j^G, E_j^G) = 1 \quad (35)$$

However, GENDA considers the composite spectrum of neutrons emitted by  $(nn'; n, 2n)$  reactions and hence,  $G(E_j^G, E_j^G)$  may be different from 1

and GENPRO proceeds to compute:

$$\mathcal{G}(E_j^G, E) = \frac{G(E_j^G, E)}{G(E_j^G, E_j^G)} \quad (36)$$

Then it locates  $E_n$  such that

$$\mathcal{G}(E_j^G, E_n) = \frac{n}{N} \text{ for } n = 0, 1, 2 \dots, N \quad (37)$$

$N$  is usually 10 for the Monte Carlo programs. The  $E_n$  are tabulated and transmitted to the EDT as Table ENN.

5. In the event of discrete level inelastic scattering, GOT supplies the  $a_\nu$ 's. The  $a_\nu^j$ 's are tabulated and transmitted to the EDT as Table PLEV ( $\nu, j$ ). The corresponding values of the excitation level energies are tabulated and transmitted to the EDT as Table ELEV ( $\nu, j$ ).

6. If both continuum and discrete level inelastic scattering occur, i.e.,  $E_{BC} < E_j^G \leq E_{BD}$ , GOT supplies information on the kernels  $g_c(E_j^G, E')$  and  $g_D(E_j^G, E')$  and the continuum and discrete level inelastic scattering cross sections,  $\sigma_{nn',c}(E_j^G)$  and  $\sigma_{nn',D}(E_j^G)$ .

To obtain the energies to which it is equally probable to scatter, the GENPRO program calculates the probability  $G(E_j^G, E)$  that a neutron at  $E_j^G$  scatters at energy  $E$  as follows:

$$G(E_j^G, E) = \frac{\sigma_{nn',c}(E_j^G) \int_0^{E_j^G} g_c(E_j^G, E') dE' + \sigma_{nn',D}(E_j^G) \int_0^{E_j^G} g_D(E_j^G, E') dE'}{\sigma_{nn',c}(E_j^G) + \sigma_{nn',D}(E_j^G)} \quad (38)$$



where  $G(E_j^G, 0) = 0$  and  $G(E_j^G, E_j^G) = 1$ , and the probability distribution functions  $g_c$  and  $g_D$  have been discussed in the GENDA section.

Then, GENPRO proceeds to locate the energies,  $E_n$ , to which it is equally probable to scatter as if the level spectrum was continuous only. The method used is similar to that of determining the cosines of the angles through which it is equally probable to scatter. The  $E_n$  are tabulated and transmitted to the EDT as Table ENN.

### 3.2 GENPRO INPUT

The input to GENPRO consists of the GENDA Output Tape (GOT) (Logical tape 9) and one card denoting the number of elements on the GOT in the format I10.

### 3.3 FORMAT OF THE EDT

A description of the format of the EDT follows. Since the EDT is made up of card images, the description is in terms of card images.

Item No.	No. of Entries	Card Description	Format
1	1	NENERG NENERG is the number of energies in the energy table.	I10
2	NENERG	ETABLE(1), ETABLE(2), ETABLE(3), ETABLE(4), ETABLE(5), ... ETABLE (NENERG). ETABLE is the energy mesh for all elements. ETABLE(1) is the lowest energy and ETABLE (NENERG) is the highest energy.	5E14.5
3	3	AWT, IAWT, J AWT is the floating point atomic weight. IAWT is the fixed point atomic weight. J is an end of data flag. $J \neq 0$ means this card is the last card of the EDT.	E16.8, 2I6

Item No.	No. of Entries	Card Description	Format
4	5	<p>OF, NOW, NFI, ISI, IPIN</p> <p>OF≠0 means this is last card of element.</p> <p>NOW is the number of words in the next group of data. NFI is a file number used for identification only. ISI≠0 means the next group of data is the scatter index.</p> <p>IPIN≠0 means this element has no inelastic scattering.</p>	E16.8, 4I6
5	NOW	<p>SIGMA(1), SIGMA(2), SIGMA(3), SIGMA(4), etc.</p> <p>SIGMA is the microscopic total cross section. Note that NOW must equal NENERG and that OF, ISI, IPIN must all be zero.</p>	5E14.5
6	5	Repeat item 4.	E16.8, 4I6
7	NOW	<p>PSCAT(1), PSCAT(2), PSCAT(3), PSCAT(4), PSCAT(5), ..., PSCAT(NENERG).</p> <p>PSCAT is the probability of elastic scattering. PSCAT(1) corresponds to ETABLE(1) and PSCAT(NENERG) corresponds to ETABLE(NENERG).</p>	5E14.5
8	5	Repeat item 4.	E16.8, 4I6
9	NOW	PABS(1), PABS(2), PABS(3), PABS(4), PABS(5), ..., PABS(NENERG).	5E14.5
10	5	<p>OF, NOW, NFI, ISI, IPIN</p> <p>ISI must equal 1 because the next data group is the scatter index. If this element has no inelastic scattering, then IPIN must equal 1.</p>	E16.8, 4I6
11	NENERG	<p>IP, ID, IT, IA</p> <p>There are NENERG cards in this data group. Each card has the quantities IP, ID, IT, IA defined as follows:</p> <p>IP = 1 for inelastic discrete scattering  = 2 for inelastic continuum scattering</p> <p>ID = the location of an ENN or PLEV table relative to the first word of the SIGMA table</p>	4I10

Item No.	No. of Entries	Card Description	Format
11	NENERG (Cont.)	IT = 1 for isotropic scattering in center of mass = 2 for scattering in hydrogen = 3 for anisotropic scattering in center of mass = 4 isotropic scattering in the lab system ID = location of a $\chi$ Table if IT = 3.	4I10
12	5	Repeat item 4 with NOW = 11.	E16.8, 4I6
13	11	CHI(1), CHI(2), CHI(3), CHI(4), CHI(5), etc. CHI is a table of 11 entries. CHI(1) = 1.0, CHI(11) = 0. Items 12, 13 are repeated for each energy at which "IT" of item 11 is 3.	5E14.5
14	5	Repeat item 4 with NOW = 11.	E16.8, 4I6
15	11	ENN(1), ENN(2), ENN(3), ENN(4), ENN(5), etc. The ENN table is used to determine the energy after scattering for an inelastic continuum interaction. Items 14 and 15 are repeated for each energy at which "IP" of item 11 is 2. If the element has no continuum scattering items, 14 and 15 are omitted.	5E14.5
16	5	Repeat item 4 with NOW = number of excitation levels for discrete scattering.	E16.8, 4I6
17	NOW	ELEV(1), ELEV(2), ELEV(3), ELEV(4), ELEV(5), ..., ELEV(NOW). The ELEV table is a list of possible excitation levels; each entry corresponds to a probability in a PLEV table.	5E14.5
18	5	Repeat item 16.	E16.8, 4I6
19	NOW	PLEV(1), PLEV(2), PLEV(3), PLEV(4), PLEV(5), ..., PLEV(NOW). The PLEV tables are tables of probabilities of scattering from the current energy to the excitation levels. Items 18 and 19 are repeated for each energy at which inelastic discrete scattering occurs (IP=1).	5E14.5

Item No.	No. of Entries	Card Description	Format
20	5	OF, NOW, ISI, IPIN OF = 1.0. NOW, ISI, IPIN = 0. Item 20 is the last card of an element.	E16.8, 4I6
21	3	AWT, IATWT, J If there are no more elements AWT, IATWT = 0. J = 1. If there are more elements repeat from item 3.	

#### 4. THE DATA ORGANIZATION PROGRAM (DATORG)

The GENDA and GENPRO programs are used to generate an element data tape (EDT) which contains microscopic cross sections and probability tables for all nuclides of interest. This EDT can be considered as a library tape for any subsequent Monte Carlo problems.

For a specific problem, however, the system is divided into regions which contain given nuclide compositions. Each composition may be described by a set of nuclides and their respective concentrations. When a particle enters collision at some point within a region of given composition, the Monte Carlo program has to select the nuclide in the composition with which the particle collides.

The probability that a particle with energy  $E$  will interact with nuclide  $k$  of the composition  $R$  is given by

$$P(k,R) = \frac{C_{k,R} \sigma_T(k,E)}{\mu_{T,R}(E)} \quad (39)$$

where  $\mu_{T,R}(E)$  is the total macroscopic cross section of the composition, and  $C_{k,R}$  is the concentration of nuclide  $k$  in region  $R$ .

$$C_{k,R} = \frac{\rho_k}{A_k} N_0 v_{k,R} \quad (40)$$

where  $\rho_k$  = density of the nuclide k

$A_k$  = its atomic weight

$N_0 10^{24} = 0.6023 \times 10^{24}$ , the Avogadro's number

$v_{k,R}$  = volume fraction of the nuclide.

#### 4.1 TECHNICAL DESCRIPTION

The DATORG program searches and reads from the EDT all information concerning the nuclides which appear in the various compositions specified in the input.

It computes the total macroscopic cross sections of each composition at each final energy,  $\mu_{T,R}(E_j^G)$ , using the concentration data supplied as input to the program.

Finally, it stores in the COMMON portion of core all data concerning the nuclides and the composition of the problem in a prescribed order.

Hence, the role of DATORG is above all the organization of the cross section and probability data read from the EDT. In addition, it computes and stores the  $\mu_{T,R}(E_j^G)$ 's.

$$\mu_{T,R}(E_j^G) = \sum_{k's \text{ in } R} C_{k,R} \sigma_T(k, E_j^G) \quad (41)$$

The output energy mesh for DATORG is, of course, given by the fixed lethargy interval used to generate the EDT.

#### 4.2 DATORG INPUT FORM

A DATORG input form is shown on the following page.

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PROJECT \_\_\_\_\_ TASK \_\_\_\_\_  
 ORIGINATOR \_\_\_\_\_  
 DATE \_\_\_\_\_  
 PROBLEM NO. \_\_\_\_\_

ADONIS INPUT FORM GROUP-1 DATA

Type Problem:  
☐ Gamma  
☐ Neutron

DATORG TITLE CARD		TITLE - ALPHABETICS AND NUMERICS ACCEPTABLE		Deck I.D. No. *
1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30
31	32	33	34	35
36	37	38	39	40
41	42	43	44	45
46	47	48	49	50
51	52	53	54	55
56	57	58	59	60
61	62	63	64	65
66	67	68	69	70
71	72	73	74	75
76	77	78	79	80
D I A T O R G				X S D I A T 1 0 1

PROBLEM IDENTIFICATION CARD (TO BE FILLED OUT ONCE ONLY)				Deck I.D. No. *
Problem number	Upper energy of cross-section data, ev	Lower energy of cross-section data, ev	No. of distinct compositions (<100)	
1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25
26	27	28	29	30
31	32	33	34	35
36	37	38	39	40
41	42	43	44	45
46	47	48	49	50
51	52	53	54	55
56	57	58	59	60
61	62	63	64	65
66	67	68	69	70
71	72	73	74	75
76	77	78	79	80
E +				X S D I A T 1 0 2

REPEAT FOLLOWING FOR EACH COMPOSITION

COMPOSITION I.D. CARD		Deck I.D. No. *
Composition number (< 100)	No. of elements (< 5)	
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15
16	17	18
19	20	21
22	23	24
25	26	27
28	29	30
31	32	33
34	35	36
37	38	39
40	41	42
43	44	45
46	47	48
49	50	51
52	53	54
55	56	57
58	59	60
61	62	63
64	65	66
67	68	69
70	71	72
73	74	75
76	77	78
79	80	81
82	83	84
85	86	87
88	89	90
91	92	93
94	95	96
97	98	99
100	101	102
X S D I A T 1 0 3		

ELEMENT CARDS		Deck I.D. No. *
Atomic weight integral point only	Concentration = $\frac{\rho N_A}{A}$ x volume fraction x $10^{24}$	
1	2	3
4	5	6
7	8	9
10	11	12
13	14	15
16	17	18
19	20	21
22	23	24
25	26	27
28	29	30
31	32	33
34	35	36
37	38	39
40	41	42
43	44	45
46	47	48
49	50	51
52	53	54
55	56	57
58	59	60
61	62	63
64	65	66
67	68	69
70	71	72
73	74	75
76	77	78
79	80	81
82	83	84
85	86	87
88	89	90
91	92	93
94	95	96
97	98	99
100	101	102
X S D I A T 1 0 4		

\*Every card is to be numbered sequentially.



### 4.3 DESCRIPTION OF THE OUTPUT DATA

The data stored by DATORG contains the following items in their order of listing.

Symbol	No. of Locations	Definition
<u>Counters</u>		
NORG	1	Counter denoting number of words in the array XSECT.
NELEM	1	Counter denoting number of distinct nuclides ( $\leq 33$ ).
NR	1	Counter denoting number of compositions ( $\leq 20$ ).
NENERG	1	Counter denoting number of energies ( $\leq 100$ ).
JK	1	Counter denoting the sum of all nuclides in every composition.
<u>Tables</u>		
NEL	NR	Number of nuclides for each composition ( $\leq 5$ for any composition).
NEVAT	NELEM	Integral value of atomic weight of each nuclide desired. Elements arranged in the order read from EDT (i.e., if oxygen = 16.0, hydrogen = 1.0, Fe = 55.85 are desired and they appear on the EDT as 16, 55.85, 1.0, then $NEL(1) = 16$ , $NEL(2) = 55$ , $NEL(3) = 1$ . Furthermore, oxygen will be referred to as element 1; Fe, as element 2, etc.).
EVAT	NELEM	Corresponding to each element in NEVAT the actual atomic weight is entered in EVAT.
IATWT	$\sum_{i=1}^{NR} NEL_i$	IATWT contains for each composition in the order of composition number the element number (see NEVAT) of each element of the composition in the order specified by the input.
CONCT	$\sum_{i=1}^{NR} NEL_i$	Corresponding to each entry in IATWT the concentration of the element is placed in CONCT.
KPHYS	NR	There is one entry for each composition and each entry contains the $N_i$ where $N_i = N_{i-1} + NEL_{i-1} + 1$ , $NEL_0 = N_0 = C$ .

Symbol	No. of Locations	Definition
XSECT	(Variable dimension)	Contains the cross section and the probabilities for each prescribed element. They are given in the order in which they are obtained in GENPRO (and appear in the EDT). Also contains macroscopic cross sections for each composition in the order of composition number.
NSECT	NELEM	Contains the origin relative to start of XSECT for each element (in the order specified by NEVAT).
MUTORG	NR	Contains origin of location of the tables of total cross sections, $\mu_T$ , in XSECT which are written in the order of composition number.

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## 5. THE GENERATION OF SOURCE PARTICLES FOR MONTE CARLO PROBLEMS

The Monte Carlo Game played in the solution of the neutron and gamma transport calculations is one in which a simulated particle is followed through all the processes with associated probability that a real particle would follow. Many such particles are tracked, and score their contribution to any physical or mathematical quantity that is desired. The tracking of a primary particle from its birth through its descendants to their disappearance from the given system (by absorption, degradation, or leakage) is defined as a history.

A particle is characterized at any instant by its space position  $\underline{P}$ , its direction  $\underline{\Omega}$ , and its energy  $E$  (neglecting effects like spin and interference phenomena).

The first step is to determine by sampling  $\underline{P}$ ,  $\underline{\Omega}$ , and  $E$  of the virgin particle from a normalized source distribution  $S(\underline{P}, E, \underline{\Omega})$ .

The volume anisotropic source generator (VANGEN) is used to select from a combination of several types of spatial, angular, and energy distributions of the primary particles.

Now, if either inelastic scatterings or absorption occur in the course of tracking neutrons, the primary Monte Carlo program (ADONIS) will record on an interaction tape the identity of the source particle which is being tracked, the location and the incident energy of the neutron at the interaction, the type of interaction,

and the element with which the neutron collided. This is done for possible secondary source generation.

The secondary gamma source particle generator (GASP) uses the interaction tape along with input data which characterize the number and energies of gammas born following an inelastic scattering or an absorption for each element to create a secondary source tape which can be used for subsequent Monte Carlo programs.

It should be noted that GASP can be used to generate other types of secondary source particles ( $\alpha$ ,  $\beta$ , fission products, ...) by judicious choice of input data. In particular, GASP has been used to create a source for neutrons produced by fission.

An important feature in the UNC Monte Carlo programs is that the generation of source particles has been arranged in such a manner that anyone with a fundamental knowledge of FORTRAN programming may create a source particle generator complying with his own needs.

### 5.1 VANGEN

VANGEN selects from a given combination of spatial, angular, and energy distributions a specified number of primary neutron or gamma source particles and records on a source tape a number which identifies the particle, its position in Cartesian coordinates, the three direction cosines of its initial direction, its energy, and the region number in which the particle was born.

There are numerous types of distributions that can be thought of, and if the need arises, a technique can be devised to select from any of them.

In the present programs, we have restricted ourselves to the more commonly used distributions.

### 5.1.1 Spatial Distributions

#### Volume Source

It is assumed that the particles are uniformly distributed in a given parallelepiped that must be fully contained in one region of the specified geometrical system. As in EZGEOM (see Section 6), the "ordinary rectangular parallelepiped" must be described by its six bounding planes:  $x_\alpha, x_\beta, y_\alpha, y_\beta, z_\alpha, z_\beta$ .

If  $\xi_1, \xi_2, \xi_3$ , are three random numbers between 0 and 1, the position of the source particle is given by:

$$\begin{aligned}x &= x_\alpha + \xi_1 (x_\beta - x_\alpha) \\y &= y_\alpha + \xi_2 (y_\beta - y_\alpha) \\z &= z_\alpha + \xi_3 (z_\beta - z_\alpha)\end{aligned}\tag{42}$$

#### Plane Source

If, in the volume source description, we make  $x_\alpha = x_\beta$  (or  $y_\alpha = y_\beta$ , or  $z_\alpha = z_\beta$ ), one obtains the uniform distribution in a plane perpendicular to one of the coordinate axes. Note that if a plane source is used, it must be inside the given source region and cannot be coincident with one of the six bounding planes of this region.

#### Point Source

If we now make  $x_\alpha = x_\beta, y_\alpha = y_\beta, z_\alpha = z_\beta$  in the volume source description and if  $x_\alpha, y_\alpha, z_\alpha$  are the coordinates of the point source, then one gets the desired distribution.

### 5.1.2 Energy Distribution

#### Method by Equal Probability Steps

If the number of source particles in energy range  $(E, E + dE)$  is given by the function  $N(E)dE$ , the input to VANGEN must be prepared as follows.

Compute the probability  $f(E)$  by any available method of integration:

$$f(E) = \frac{\int_{E_0}^E N(E)dE}{\int_{E_0}^{E_{\max}} N(E)dE} \quad (43)$$

where  $E_0$  and  $E_{\max}$  are the lower and upper energies of the distribution respectively.

Hence,  $f(E_0) = 0$ ,  $f(E_{\max}) = 1$ .

Determine the  $E_\eta$ 's such that

$$(E_\eta) = \frac{\eta}{M} \text{ for } \eta = 0, 1, \dots, M \quad (44)$$

where  $M$  is the number of equal probability steps that is selected ( $M < 100$ ).

The input will consist of the number of equal probability steps plus 1 ( $M+1$ ), the width of the probability interval ( $1/M$ ) and the upper and lower energy limits of each step (i.e., for step  $\eta$ ,  $E_{\eta-1}$  and  $E_\eta$ ).

The program will select a random number,  $\xi$ , between 0 and 1 and take the integral portion of  $1 + [\xi/(1/M)] = 1 + M\xi$ . This will determine the energy bin in which the energy of the source neutron must be selected. For example, if the integral portion of  $1 + M\xi$  is equal to  $\eta$ , the  $E_{\eta-1} \leq E \leq E_\eta$ . In the energy bin itself, the energy  $E$  is selected assuming a uniform distribution.

$$E = E_{\eta-1} + \alpha(E_\eta - E_{\eta-1}) \quad (45)$$

where

$$\alpha = \frac{\xi - [M\xi] \frac{1}{M}}{\frac{1}{M}}$$

with  $[M\xi]$  = integral portion of  $M\xi$ .

### Fission Spectrum

The number of neutrons in the energy range  $(E, E + dE)$  is given by

$$N(E)dE = A e^{-\alpha_1 E} \sinh \sqrt{\alpha_2 E} dE \quad (46)$$

where  $\alpha_1$ ,  $\alpha_2$ , and  $A$  are constants and  $E_L < E < E_U \geq 0$  and  $E_U \leq \infty$  are the lower and the upper limits of the fission spectrum respectively.

The method described in the foregoing section may be applied. However, the program uses an elegant rejection technique invented by M.H. Kalos<sup>6</sup> in order to pick  $E$  from the probability distribution given by Eq. 46.

Briefly, an energy  $E$  is chosen as follows.

Suppose

$$p_1(x)dx = \frac{e^{-x}dx}{e^{-x_1} - e^{-x_2}} \quad x_1 \leq x \leq x_2 \quad (47)$$

$$p_2(y)dy = e^{-y} dy \quad 0 \leq y < \infty \quad (48)$$

If

$$-ax + (y - bx - c)^2 \leq 0, \quad (49)$$

choose

$$E = \gamma x \quad (50)$$



Otherwise, reject and repeat from Eq. 47.

To obtain the right fission distribution and insure a maximum efficiency for the rejection technique, the parameters  $a$ ,  $b$ ,  $c$ ,  $\gamma$  have been evaluated using the latest experimental fit for the fission spectrum of prompt neutrons.

$$a = 4.572573$$

$$b = 1.069179$$

$$c = 1.069179$$

$$\gamma = 1.99675$$

and in Eq. 46,

$$x_1 = \frac{E_L}{\gamma} \quad x_2 = \frac{E_U}{\gamma}.$$

### Monoenergetic Source

If the upper and lower limits of the fission spectrum are made equal to the desired energy, one obtains the monoenergetic distribution.

### 5.1.3 Angular Distribution

#### Anisotropic Angular Distribution

If the angular distribution of the source particles is symmetric about an axis,  $\underline{\Omega}_0$ , one can divide the total solid angle into  $M$  intervals, each interval being defined by the scalar product of the angle of the cones with  $\underline{\Omega}_0$ , i.e., interval  $i$  is defined by  $W_{i-1}$  and  $W_i$  such that

$$\begin{aligned} W_{i-1} &= \underline{\Omega}_{i-1} \cdot \underline{\Omega}_0 \\ W_i &= \underline{\Omega}_i \cdot \underline{\Omega}_0 \end{aligned} \tag{51}$$

In each of these intervals, the number of source particles is given with probability  $p_i$ ; such that

$$\sum_{i=1}^M p_i = 1.$$

The program will select a random number  $\xi$  between 0 and 1, and compare it to

$$\sum_{i=1}^j p_i,$$

where  $j \leq M$ .

If

$$\sum_{i=1}^{j-1} p_i \leq \xi \leq \sum_{i=1}^j p_i, \quad (52)$$

then the direction of the source particle is selected from the  $j^{\text{th}}$  interval.

The direction cosine in the  $j^{\text{th}}$  interval is then chosen with equal probability. Thus

$$W = W_{i-1} + \xi' (W_i - W_{i-1}). \quad (53)$$

where  $\xi'$  is another random number.

The azimuthal angle is also chosen at random between 0 and  $2\pi$ .

### Isotropic Angular Distribution

The isotropic case is obtained by making  $M = 1$ ,  $W_0 = -1$ ,  $W_1 = +1$ , and  $p_1 = 1$  in the anisotropic distribution.

### Monodirectional Distribution

In this case, it is sufficient to take  $M = 1$ ,  $W_0 = W_1 = \pm 1$  and  $p_1 = 1$  in the anisotropic distribution. Of course, directions parallel to each coordinate axis in both positive and negative directions can be obtained by choosing the axis direction,  $\underline{\Omega}_0$ .

The numbers 1, 2, or 3 submitted as input indicate that the source will be generated about the x, y, or z axis respectively.

### 5.2 GASP

GASP selects the energy of secondary gammas produced by neutron inelastic scattering and absorption which includes capture, fission, and production following a charged particle reaction. The position of these secondary source gammas is read from the interaction tape and their direction can be selected as in VANGEN. The output is written on the source tape.

For each element of interest (specified by the integral part of its mass number) for both absorption and inelastic scattering and for a given number of energy intervals for the incident neutrons, the GASP data input consists of

1. A table which contains the gamma energies in increasing order,  
 $E_{\gamma\ell} \quad \ell = 1, 2, \dots, L \leq 10.$
2. A table which lists the lower and upper energies of the neutron bin intervals,  $E_k$ ,  $k = 0, 1, \dots, K \leq 30$ , such that the  $k^{\text{th}}$  energy bin is given by the interval  $(E_{k-1}, E_k)$ .
3. A list of the expected number of gammas of energy  $E_{\gamma\ell}$  born in an interaction with a neutron whose initial energy lies in the interval  $(E_{k-1}, E_k)$ ,  
 $N_{\gamma\ell,k}$

The GASP program proceeds to select  $L$  random numbers,  $\xi_1, \xi_2, \dots, \xi_\ell, \dots, \xi_L$ . The integral part of  $N_{\gamma\ell,k}$  plus a Russian roulette method for the fractional portion is used to determine the number of source gammas at energy  $E_{\gamma\ell}$ . For in-

stance, if  $N_{\gamma\ell,k} = 3.5$  and  $\xi_\ell$  is the corresponding random number,  $\xi_\ell$  is compared to 0.5. If  $\xi_\ell > 0.5$ , then four gammas are taken with energy  $E_{\gamma\ell}$ . If  $\xi_\ell < 0.5$ , three gammas are taken with energy  $E_{\gamma\ell}$ .

Further, if, in the ADONIS problem, weights  $W_n$  and  $W_\gamma$  are attached to the region in which the interaction takes place, the number of gammas obtained is multiplied by the ratio  $W_n/W_\gamma$ , and the number of source gammas is obtained again by taking the integral fraction of the product plus the result of the Russian roulette played with the fractional portion of the product.

Gamma production by radiative neutron capture, fission, and charged particle reaction, i.e., (N,P), must be included in the input for the gamma production by absorption.

Thus, the input must be the expected number of gammas born by neutron absorption given by

$$N_{\gamma\ell}^A = \frac{\sigma_\ell^c N_{\gamma\ell}^c + \sigma_\ell^F N_{\gamma\ell}^F + \sigma_\ell^P N_{\gamma\ell}^P}{\sigma_\ell^c + \sigma_\ell^F + \sigma_\ell^P} \quad (54)$$

where  $\sigma$  denotes a cross section and the superscripts c, F, A, and P denote capture, fission, absorption, and charged particle reaction, respectively.

### 5.3 VANGEN INPUT DESCRIPTION

The VANGEN input is described as follows (columns 73 to 80 are for identification):

#### 5.3.1 Card 1 (contains parameter input for VANGEN)

Column	Item	Format
1-10	The number of source particles to be generated.	I
15	The normal direction of the source: 1 = x-direction, 2 = y-direction, 3 = z-direction	

Column	Item	Format
18-20	The number of the region where the source particle will be born.	I
23-25	If the energy distribution is chosen at equal probability intervals, this entry contains the number of energy intervals + 1. If the fission spectrum option or monoenergetic option is desired, the entry is 0.	I
26-37	The entry for the upper energy limit of the fission spectrum desired, $E_U$ (0 if this option is not desired).	E
38-49	The entry for the lower energy limit of the fission spectrum desired, $E_L$ (0 if this option is not desired).	E

Note:

For monoenergetic problems,  $E_U = E_L$  and entries in the columns 23 through 25 should be 0.

5.3.2 Card 2 (contains the desired spatial distribution)

Column	Item	Format
1-12	The $x_\alpha$ bounding plane of the source volume.	6E12 ↓
12-24	The $x_\beta$ bounding plane of the source volume.	
25-36	The $y_\alpha$ bounding plane of the source volume.	
37-48	The $y_\beta$ bounding plane of the source volume.	
49-60	The $z_\alpha$ bounding plane of the source volume.	
61-72	The $z_\beta$ bounding plane of the source volume.	

Notes:

1. If  $x_\alpha = x_\beta$ , or  $y_\alpha = y_\beta$ , or  $z_\alpha = z_\beta$ , plane source distribution is obtained.
2. If  $x_\alpha = x_\beta$ ,  $y_\alpha = y_\beta$  and  $z_\alpha = z_\beta$ , point source distribution is obtained.

At the present time, the spatial distribution must be contained in one and only one region.

The next set of cards contains information on the energy distribution in equal probability steps if desired. (Use only if columns 23 to 25 on card 1 are nonzero.)

The first entry is the probability step. It is then followed by the energies (in ev) in increasing order. (These energies are the limits of energy bins.) The number of energies is one more than the number of bins. There are six entries per card. The format is 6E12,5.

Three types of cards describe the angular distribution:

1. The Bin Information Card

Contains the number of angular bins + 1 in columns 3-4.

2. The Angular Bin Card

These cards contain the cosine limits of each angular bin. There are seven entries per card and the format is 7E10,4. [The lower limit of the  $(i+1)^{th}$  bin is the upper limit of  $i^{th}$  bin.]

3. The Probability Card

The first entry is 0 and each entry contains the corresponding probability for each angular bin starting with the first angular bin. There are seven entries per card and the format is 7E10,4.

Note:

If an isotropic source in the forward half plane is desired, only one angular bin is necessary. The input then is:

Card type 1	2	Two cosines define bin 1
Card type 2	0.0 1.0	The lower and upper limits of the bin
Card type 3	0 1.0	The probability that a particle will be born in bin 1 is 1.

## 5.4 GASP INPUT DESCRIPTION

The GASP input is described as follows:

### 5.4.1 Element Parameter Card

This card contains the number of elements used in the associated ADONIS problem. The format is I5.

### 5.4.2 Element Input Data (for each element)

#### 1. Element Parameter Card

Column	Item	Format
1-6	Integral part of the atomic mass (identification of element same as that specified in DATORG input)	
6-10	$L_A$ = number of absorption gamma output energies ( $\leq 10$ ) (0 if no capture $\gamma$ produced)	I
11-15	$K_A$ = number of corresponding incident neutron energies ( $\leq 30$ ). This equals the number of neutron energy bins + 1 (0 for no $\gamma$ capture).	I
16-20	$L_I$ = number of inelastic $\gamma$ out energies ( $\leq 10$ )	I
21-25	$K_I$ = number of corresponding incident neutron energies ( $\leq 30$ ). This equals the number of neutron energy bins + 1.	I

#### 2. Capture $\gamma$ Energy Cards (as many as necessary)

The energies are given in ascending order in ev. The number of entries per card is six and the format is 6E12.6. The total number of entries is equal to  $L_A$ .

#### 3. Capture Neutron Energy Cards (as many as necessary)

Every two entries represent a neutron energy bin. The entries are in ascending order and in ev. There are six entries per card and the format is 6E12.6.

#### 4. Capture Number Cards

Each entry represents the number of gammas produced at each of the specified  $\gamma$  energies. These numbers are entered for each neutron energy bin. The first  $L_A$  entries are 0 representing the 0<sup>th</sup> bin.

Start a new card for each neutron bin. There are six entries per card and the format is 6E12,6.

Repeat items 2, 3, and 4 for inelastic scattering input, if any.

#### 5.4.3 Weights for Neutron and Gamma Problem Input (See Section 7.3.1)

##### 1. Number of Regions Card

Enter the number of regions used in the associated neutron and gamma problems (I5 format).

2. Enter the weight for each region used in the neutron problem (format 5E14,8). (Note: there is only one entry per region. At the present time one cannot use energy importance in the neutron problem and run the secondary  $\gamma$ -ADONIS. It is anticipated that this restriction will be removed in the near future.)

3. Enter the weight for each region to be used in the secondary gamma problem (format 5E14,8).

#### 5.4.4 Angular Distribution

The angular distribution input is the same as for VANGEN.

#### 5.5 DESCRIPTION OF THE SOURCE TAPE

The source tape which is generated by both VANGEN and GASP must conform to the specifications required by the ADONIS program. Particles must be generated in groups of 100. Each particle is described by nine numbers:



- 1        the particle number
- 2-4     the location of the particle in 3-space (its x-y-z coordinates)
- 5-7     the three direction cosines the particle assumes initially
- 8        the initial energy of the particle
- 9        the region number in which the particle is born.

With the exception of the particle number and the region number, the entries are in floating point notation, and are generated by a FORTRAN routine using the "WRITE TAPE" statement for 100 particles, with nine entries for one particle preceding the nine entries for the next. Finally, to signal the end of the source particles that one wants to generate, one additional particle whose particle number is -1 is necessary.

#### 5.6 SOURCE INPUT

The source input consists of either VANGEN or GASP input forms. See following pages.

This Document Contains  
Missing Page/s That Are  
Unavailable In The  
Original Document

OR are  
Blank pgs.  
that have  
Been Removed

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AVAILABLE COPY**

ADONIS SOURCE GENERATOR  
VANGEN

VANGEN TITLE CARD		TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)	Card I.D. No.
1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16
17	18	19	20
21	22	23	24
25	26	27	28
29	30	31	32
33	34	35	36
37	38	39	40
41	42	43	44
45	46	47	48
49	50	51	52
53	54	55	56
57	58	59	60
61	62	63	64
65	66	67	68
69	70	71	72
73	74	75	76
77	78	79	80
V	A	N	G
0	0	0	1

ADONIS SOURCE GENERATOR (CONTINUED)  
VANGEN

Page 2 of 3

PROBLEM INFORMATION CARD (ONCE ONLY)					E lower of fission spectrum, ev (see note)	E upper of fission spectrum, ev	Card I.D. No.
No of source particles to be generated (~ 250,000)	Normal direction of source	Region no. of points (~ 80)	No. of energies to be specified (~ 100)				
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

Note: Fill in only if No. of energies to be specified is = 0.

COORDINATE OF SOURCE CARD (ONCE ONLY)				Card I.D. No.
X <sub>α</sub> coordinate	X <sub>β</sub> coordinate	Y <sub>α</sub> coordinate	Y <sub>β</sub> coordinate	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

ENERGY CARD (AS MANY CARDS AS NEEDED)				Card I.D. No.*
First card: probability step of energy distribution. All other cards: continuation of energy values.	Energy, ev Lowest value first	Energy, ev	Energy, ev	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

\*No. sequentially

ADONIS SOURCE GENERATOR (CONTINUED)  
VANGEN

Page 3 of 3

BIN INFORMATION CARD (ONCE ONLY)		Card I.D. No.
No. of angles ( $\leq 25$ )		
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80		V I A N G E N I

ANGULAR BIN CARD (AS MANY AS NECESSARY)						Card I.D. No.*
$\cos \phi = \omega$ (see note)	$\cos \phi = \omega$	$\cos \phi = \omega$	$\cos \phi = \omega$	$\cos \phi = \omega$	$\cos \phi = \omega$	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80						V I A N G E N I

NOTE: Two consecutive entries correspond to an angular probability bin  
(i.e., 24 bins = 25 entries)

PROBABILITY PER BIN CARD (SAME NUMBER AS ABOVE)		Card I.D. No.*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80		V I A N G E N I

\*No. sequentially

# ADONIS SOURCE GENERATOR

GAMMA SOURCE PRODUCTION (GASP)  
Page 1 of 8

GASP TITLE CARD		ANY KIND OF TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)	Card I.D. No.
1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16
17	18	19	20
21	22	23	24
25	26	27	28
29	30	31	32
33	34	35	36
37	38	39	40
41	42	43	44
45	46	47	48
49	50	51	52
53	54	55	56
57	58	59	60
61	62	63	64
65	66	67	68
69	70	71	72
73	74	75	76
77	78	79	80
GASP		GASP	

CONTINUATION OF GASP  
Page 2 of 8

[illegible]

UNTIL NOTED OTHERWISE, REPEAT ALL OF THE FOLLOWING CARDS FOR EACH ELEMENT

ELEMENT CARDS (ONE PER ELEMENT)					Card I.D. No.*
Integral part of mass No.	No. of capture $\gamma$ energies (- 10)	No. of capture neutron energies (- 30)	No. of inelast. $\gamma$ energies (- 10)	No. of inelast. neutron energies (- 30)	
1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25	73 174 175 176 177 178 179 180

•No. sequentially

[illegible]

CAPTURE NEUTRON ENERGY CARDS (AS MANY AS NECESSARY)										Energy, ev	Energy, ev	Energy, ev	Energy, ev	Card I.D. No.*
Energy, ev	Energy, ev	Energy, ev	Energy, ev	Energy, ev	Energy, ev	Energy, ev	Energy, ev	Energy, ev						
1 2 3 4 5	6 7 8 9 10 11 12	13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48												
•	E <sub>1</sub>	• E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	G <sub>1</sub> A <sub>1</sub> S <sub>1</sub> P <sub>1</sub>
•	E <sub>1</sub>	• E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	G <sub>1</sub> A <sub>1</sub> S <sub>1</sub> P <sub>1</sub>
•	E <sub>1</sub>	• E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	G <sub>1</sub> A <sub>1</sub> S <sub>1</sub> P <sub>1</sub>
•	E <sub>1</sub>	• E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	G <sub>1</sub> A <sub>1</sub> S <sub>1</sub> P <sub>1</sub>
•	E <sub>1</sub>	• E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	E <sub>1</sub>	•	G <sub>1</sub> A <sub>1</sub> S <sub>1</sub> P <sub>1</sub>

•No. sequentially



[illegible]

\* no. sequentially

ADONIS SOURCE GENERATOR (CONTINUED)

INELASTIC GAMMA ENERGY CARDS (AS MANY AS NECESSARY)										Card I.D. No.*
1	2	3	4	5	6	7	8	9	10	
1	2	3	4	5	6	7	8	9	10	73 74 75 76 77 78 79 80
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P

INELASTIC NEUTRON ENERGY CARDS (AS MANY AS NECESSARY)										Card I.D. No.*
1	2	3	4	5	6	7	8	9	10	
1	2	3	4	5	6	7	8	9	10	73 74 75 76 77 78 79 80
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P
•	•	•	•	•	•	•	•	•	•	G A S P

\*No. sequentially

## ADONIS SOURCE GENERATOR (CONTINUED)

DISCONTINUE REPEAT FOR EACH ELEMENT INSTRUCTION

REGION CARD (ONCE ONLY)		Card ID No *
No of regions in problem		
1	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	G I A S I P

NEUTRON WEIGHT PER REGION CARDS				Card ID No *
In ascending reg order	Weight	Weight	Weight	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	G I A S I P

GAMMA WEIGHT PER REGION CARDS				Card ID No *
Weight	Weight	Weight	Weight	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80	G I A S I P

\*No sequentially

# ADONIS SOURCE GENERATOR (CONTINUED)

CONTINUATION OF GASP  
Page 8 of 8

BIN INFORMATION CARD (ONCE ONLY)		Card I.D. No.
No. of angles ( $\leq 25$ )		
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25		73 74 75 76 77 78 79 80
		G A S P

ANGULAR BIN CARD (AS MANY AS NECESSARY)					Card I.D. No.*
$\cos \phi = \omega$ (see note)	$\cos \phi = \omega$	$\cos \phi = \omega$	$\cos \phi = \omega$	$\cos \phi = \omega$	
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25					73 74 75 76 77 78 79 80
					G A S P
					G A S P
					G A S P
					G A S P

NOTE: Two consecutive entries correspond to an angular probability bin  
(i.e., 24 bins = 25 entries)

PROBABILITY PER BIN CARD (SAME NUMBER AS ABOVE)					Card I.D. No.*
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25					73 74 75 76 77 78 79 80
					G A S P
					G A S P
					G A S P
					G A S P

\*No. sequentially

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Original Document

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that have  
Been Removed

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## 6. THE ORGANIZATION OF THE GEOMETRY DATA (EZGEOM)

Monte Carlo programs track simulated particles through a specified geometrical configuration, undergoing all the interactions that an actual particle is expected to undergo. The particle flight may pass through media having different properties. Therefore, it is of primary importance to know at all times in which medium the particle is, when the particle leaves the medium, and which medium it will be entering. Different media may be described as containing given material compositions in three-dimensional geometrical figures.

However, it is necessary to decompose these figures into particular geometrical forms which can be handled by the ADONIS program, i.e., nonintersecting rectangular parallelepipeds, right cylinders, spheres, and right wedges.

The EZGEOM program processes the input which consists of the description of the desired configuration by means of these elementary geometrical forms and stores the information into tables for rapid data access in subsequent Monte Carlo programs.

### 6.1 DEFINITIONS AND NOTATION

The three-space coordinate system used in describing the geometry is a Cartesian right-handed coordinate system. The  $x$ ,  $y$ ,  $z$  directions will be described as  $x_1$ ,  $x_2$ ,  $x_3$ .

The entire three-dimensional space is initially decomposed into a set of rectangular parallelepipeds whose bounding planes are parallel to the coordinate axes. These parallelepipeds are called ordinary regions and are described by the coordinates of their six bounding planes:  $x_i^\alpha, x_i^\beta$  with  $i = 1, 2, 3$  and  $x_i^\alpha \leq x_i^\beta$ .

Any elementary geometrical form which is completely described in the input by a vertex  $V(x_1, x_2, x_3)$  and a set of vectors and scalars is called a nonordinary region. Nonordinary regions presently handled by EZGEOM and geometry tracking routines are spheres, right cylinders, rectangular parallelepipeds, and right wedges. In the near future, right frusta of cones will be handled by these routines.

Due to storage restrictions and word length requirements, the following rules must be observed when preparing EZGEOM input.

1. Nonordinary regions must be wholly contained in either an ordinary or a nonordinary region. Due to possible round-off errors, it is suggested that no surface of a contained region be closer to any surface of the containing region than  $10^{-6}$  times the maximum coordinate found on the surface of the containing region. Note that the geometry is first decomposed into ordinary regions. Hence, a nonordinary region may contain a set of nonordinary regions, but must eventually be itself part of a set of regions which are wholly contained in an ordinary region.
2. The total number of ordinary and nonordinary regions must be less than or equal to 200.
3. At most, 127 nonordinary regions may be used.
4. A nonordinary region I must be wholly contained in another region E. Let region E be defined as the region external to I. At the most, seven such regions may have E as an external region. We will say that any region



may see only seven regions. In turn, each of these regions may see, at most, seven regions.

5. The geometry input must be submitted as follows:

First, define the ordinary regions and number them from 1 to  $M$ ,  $M$  being the number of ordinary regions.

Then, define the nonordinary regions (by geometrical category and coordinate data) and number them starting from  $M + 1$ .

6. The data required to describe the nonordinary regions for the input are:

a. Spheres

Specify the vertex  $V$  at the center and the scalar  $R$  denoting the radius.

b. Right Cylinders

Specify the vertex  $V$  at the center of one base, a height vector,  $\underline{H}$ , expressed in terms of its components, and a scalar  $R$  denoting the base radius.

c. Rectangular Parallelepipeds

Specify the vertex  $V$  at one of the corners and a set of three mutually perpendicular vectors,  $\underline{\alpha}_i$ , representing the height, width, and length of the parallelepiped respectively. Note that the bounding planes need not be parallel to the coordinate axes.

d. Right Wedges

The input is the same as for the nonordinary rectangular parallelepipeds. However, the first two vectors describe the two legs of the right triangle of the wedge.

#### e. Right Frusta of Cones

Specify a vertex  $V$  at the center of the lower base, the height vector,  $\underline{H}$ , expressed in terms of its components, and two scalars,  $R_1$  and  $R_2$ , denoting the radii of the lower and upper bases respectively. (The frusta of cones is expected to be included in the geometry description in the near future.)

### 6.2 TECHNICAL DESCRIPTION

The EZGEOM routine considers first the ordinary regions and proceeds to find the regions adjacent to each side of the ordinary parallelepipeds, starting with region number 1.

Let  $x_{i,m}^\alpha, x_{i,m}^\beta$  be the coordinates of the six bounding planes of the ordinary region,  $m$  ( $1 \leq m \leq M$ ,  $M$  being the total number of ordinary regions). The routine starts with  $x_{1,1}^\alpha$  and compares it to  $x_{1,m}^\beta$  for  $m = 2, 3, \dots, M$ .

Suppose that  $x_{1,1}^\alpha = x_{1,m}^\beta$ , then the  $x_1^\alpha$  face of region 1 and the  $x_1^\beta$  face of region  $m$  are on the same plane. This case is illustrated by Fig. 4.

It is necessary to determine whether or not the two faces have an area in common. Hence, the program proceeds to test:

1.  $x_{2,1}^\alpha: x_{2,m}^\beta$ . If greater than or equal, there is no overlap and the routine considers the next region (Fig. 4 and case a of Fig. 5). If less than, then the second test is tried.
2.  $x_{2,1}^\beta: x_{2,m}^\alpha$ . If less than or equal, there is no overlap and the routine considers the next region (case a, Fig. 5). If greater than, then the third test is tried.

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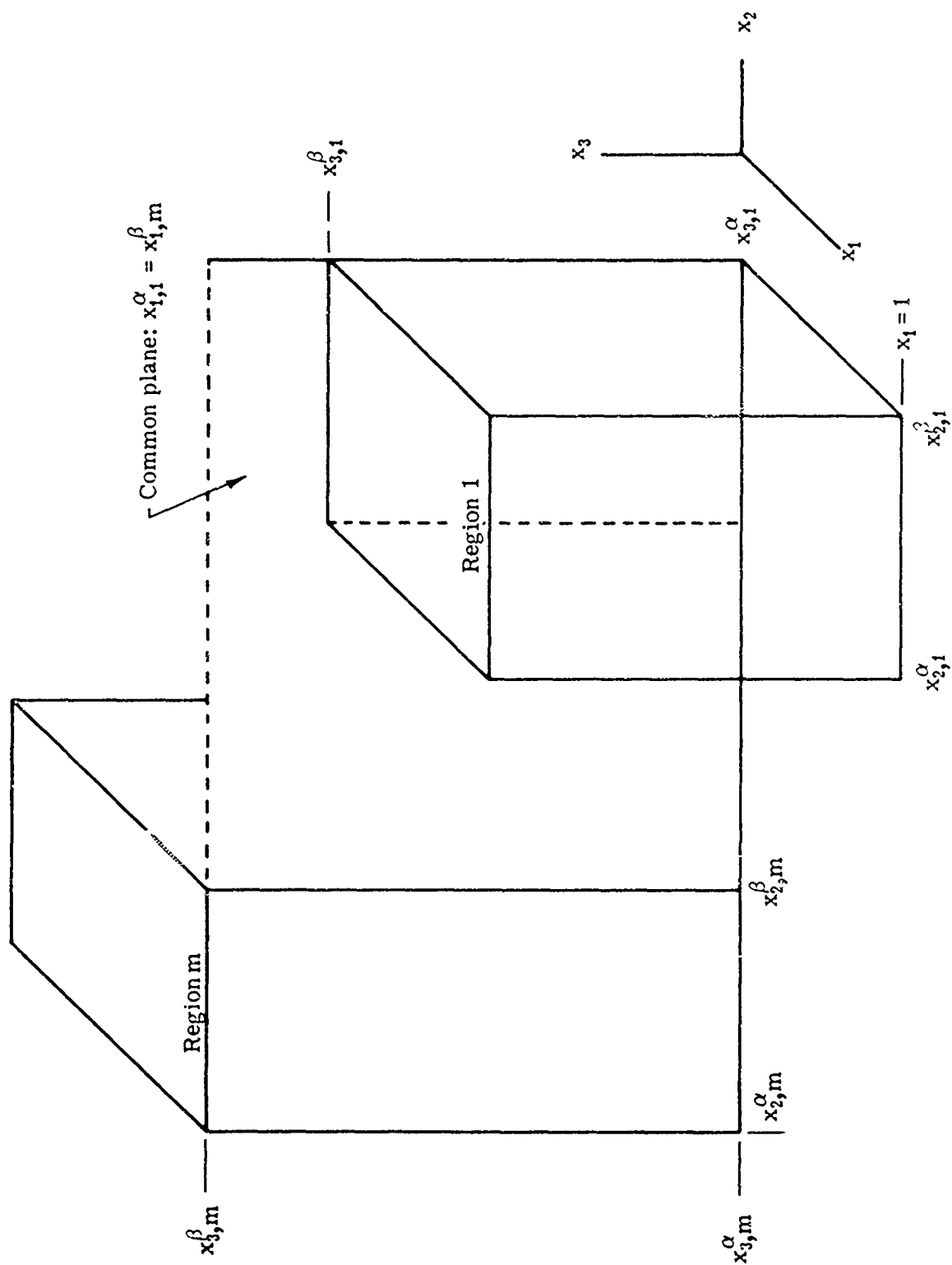


Fig. 4 — Case where regions 1 and m have a face lying in a common plane ( $x_1^\alpha = x_1^\beta$ ) with no overlapping

Case a(No overlapping in the  $x_2$  direction)

$$(x_{2,1}^\alpha \geq x_{2,m}^\beta)$$

Case b(Overlapping in the  $x_2$  direction but no overlapping in the  $x_3$  direction)

$$x_{2,1}^\alpha < x_{2,m}^\beta$$

$$x_{2,1}^\beta > x_{2,m}^\alpha$$

$$x_{3,1}^\alpha > x_{3,m}^\beta$$

Case c(Overlapping in both the  $x_2$  and  $x_3$  directions)

$$x_{2,1}^\alpha < x_{2,m}^\beta$$

$$x_{2,1}^\beta > x_{2,m}^\alpha$$

$$x_{3,1}^\alpha < x_{3,m}^\beta$$

$$x_{3,1}^\beta > x_{3,m}^\alpha$$

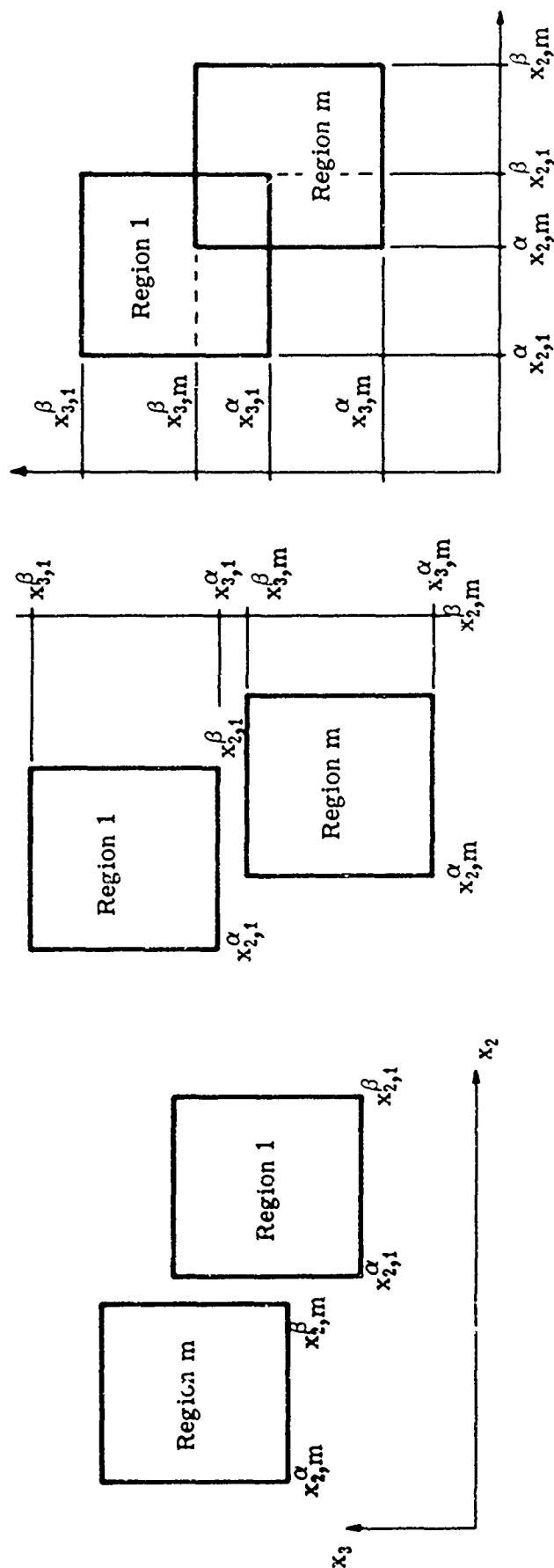


Fig. 5 — Case where regions 1 and m have a face lying in a common plane ( $x_{1,1}^\alpha = x_{1,m}^\alpha$ )

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3.  $x_{3,1}^{\alpha} : x_{3,m}^{\beta}$ . If greater than or equal, there is no overlap (case b, Fig. 5) and the comparison to the  $m + 1$  region is considered. If less than, then the fourth and last test is tried.
4.  $x_{3,1}^{\beta} : x_{3,m}^{\alpha}$ . If less than or equal, there is no overlap (case b, Fig. 5) and the comparison to the  $m + 1$  region is considered. If greater than, then there is an area in common (case c, Fig. 5). In this case, the region  $m$  is stored in a table in which all regions adjacent to region 1 are recorded.

Once the comparison of  $x_{1,1}^{\alpha}$  to  $x_{1,m}^{\beta}$  for all  $m$  is completed, the number of regions contained in the table is tested.

1. If there is no adjacent region, the coordinate  $x_{1,1}^{\alpha}$  is an extremity for the geometry and the region adjacent to region 1 on the  $x_1^{\alpha}$  face is itself. This coordinate is saved. Then, if in the course of the investigation of the  $x_1^{\alpha}$  coordinate of other regions another extremity is found which is not equal to  $x_{1,1}^{\alpha}$ , it means that the geometry has not been properly defined. This diagnostic is printed, and the program is stopped.
2. If there is only one region, the region number is placed in the proper table as the region adjacent to region 1 on the  $x_1^{\alpha}$  face. Further, a flag is set to denote that region 1 is adjacent to that region, say region  $m$ . Thus, when the  $x_1^{\beta}$  face of region  $m$  will be investigated, there is no need to search for regions in contact with it if their region number is less than  $m$ . The procedure is followed for regions whose number is greater than  $m$  only.
3. If there is more than one region in contact with the  $x_{1,m}^{\alpha}$  face of a given region, the  $x_{1,m}^{\alpha}$  face is defined as a complex surface. The EZGEOM program proceeds to decompose the complex surface into a grid of elementary rectangles and assign to each of them the corresponding region number.

Let us consider the complex surface oriented such that the normal to that plane is in the positive direction. The horizontal and the vertical directions are determined, using the right-handed method, i.e., if the  $x_2$ -axis is normal to the complex surface as in the case shown in Fig. 6, then the  $x_1$  and  $x_3$  axes are the horizontal and vertical directions respectively.

The first step performed by the routine is to extract the  $\beta$  coordinates in the horizontal direction of all adjacent regions and place them in increasing order removing duplicated coordinates, say  $H_1, H_2, \dots, H_{\max}$ .

The second step is to test if  $H_{\max}$  is greater than or equal to  $x_2^\beta$  of the region investigated. If it is,  $x_2^\beta$  replaces  $H_{\max}$  in the table. If it is less, this means that there is an area on the right side of the face which has not been accounted for. A diagnostic is printed pointing out that a hole exists and the program is stopped.

The same sequence of operations is performed for the  $\beta$  coordinates in the vertical direction, say  $V_1, V_2, \dots, V_{\max}$ .

These horizontal and vertical sequences determine a two-dimensional matrix. The complex surface is thus decomposed in a grid of rectangles. The EZGEOM program proceeds to place in each of these rectangles the corresponding region number. It must be noted that several rectangles may belong to a given region. This is done as follows: let  $x_{2,m}^\alpha, x_{2,m}^\beta$  be the coordinates in the horizontal direction of the adjacent region  $m$ . The program determines the number of intervals  $H_i$  contained in  $[x_{2,m}^\alpha, x_{2,m}^\beta]$ . Clearly, there must be horizontal coordinates in the horizontal sequence which equal to  $x_{2,m}^\alpha$  and  $x_{2,m}^\beta$ . If not, either a hole or an overlap exists and a diagnostic is printed giving the region number under consideration, the plane being searched, the table of adjacent regions found, and the horizontal and vertical tables. From this information, it is possible to construct the complex surface and find the error.



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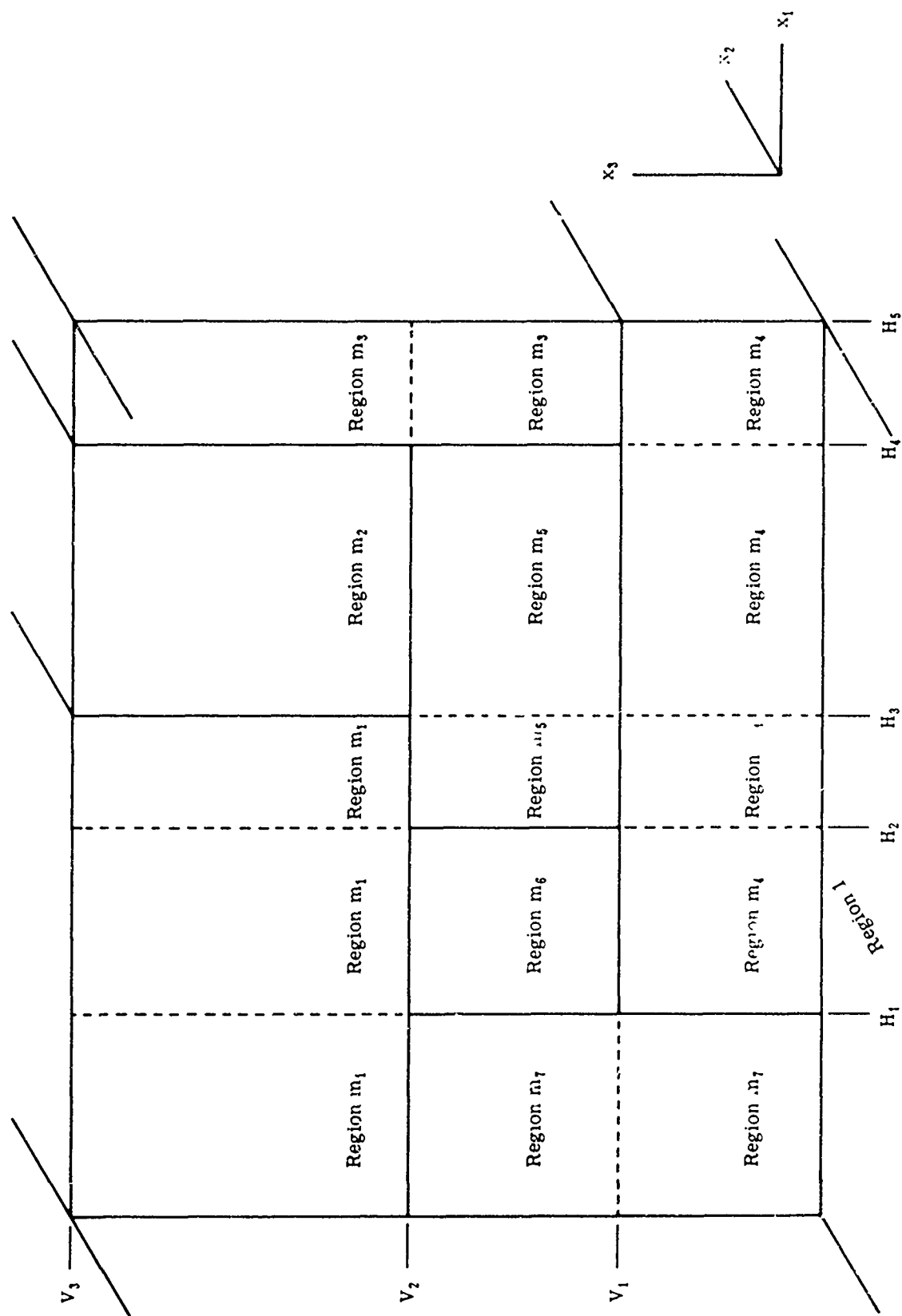


Fig. 6 — Illustration of the EZGEOM decomposition of a complex surface

If no error has occurred, the data gathered for the complex surface are placed in Table 3 which is described in Section 6.3.

The same procedure is repeated for each face of each region.

When all ordinary regions have been processed, the input cards for the nonordinary regions are read and stored according to the format described in Section 6.3.

At the present time, there is no routine built into EZGEOM which verifies that the submitted input for the nonordinary region is properly defined. Consequently, extreme care should be taken in preparing input data for nonordinary regions.

In conclusion, it is believed that EZGEOM will find most, if not all, errors made in the input data for ordinary geometry. It is possible for EZGEOM to fail to give a diagnostic when the programmed dimensions of a table for complex surfaces are exceeded. This may occur when a complex surface is defined by a grid of more than  $20 \times 20$  rectangles and the investigated region is located near the end of the ordinary region listing. This is an instance when an incorrect edit can be obtained. In this case, all the regions adjacent to region 1 will be called region 1, showing that the geometry was handled incorrectly. In general, the situation is improved by assigning a very low region number to that region.

## 6.3 DESCRIPTION OF THE INPUT-OUTPUT

### 6.3.1 Input

1. The first card contains the number of ordinary regions,  $M$ , and the number of nonordinary regions,  $N$  ( $N \leq 127$ ). Note that  $M + N \leq 200$ .
2. The next  $M$  cards contain the coordinates of the six bounding planes of each region:  $x_i^\alpha, x_i^\beta; i = 1, 2, 3; x_i^\alpha < x_i^\beta$ . Note that the cards are placed in the same order as the region numbers.

3. The input for each of the  $N$  nonordinary regions has been described in the definitions (Section 6.1). The order in which the cards are placed is also according to the region numbers ( $M + 1$  to  $N + M$ ).

### 6.3.2 Output

The output edit gives a complete description of each region and is self-explanatory.

EZGEOM generates three tables which completely describe the geometry specifications for the problem. The data in these tables are arranged so that they are rapidly accessible to the Monte Carlo tracking routines.

### Table 1

There is an entry in Table 1 corresponding to each region of the problem. (The  $i^{\text{th}}$  entry corresponds to the  $i^{\text{th}}$  region.) Each entry to Table 1 is packed into 35 bits as follows.

1. The first three high order bits contain the number of internal regions that the region sees (see Section 6.1). The maximum number of such regions for any given region is seven.
2. The next three bits describe the type of region
  - 0 = ordinary parallelepiped
  - 1 = sphere
  - 2 = cylinder
  - 3 = wedge
  - 4 = nonordinary parallelepiped
  - 5 = frusta of cone.
3. The next eight bits contain the number of the region external to the region. This only applies to nonordinary regions, types 1-5).
4. The next seven bits contain a location relative to Table 2 where the regions whose external region is the region considered are listed. The entry is zero when there are no such regions.

5. The last 14 bits contain the location relative to Table 3 where the region data are listed.

#### Table 2

This table contains an entry for each of the nonordinary regions (types 1-5), and these entries are grouped corresponding to their external region. Each entry is packed into 25 bits as follows.

1. The first three bits contain the type of the region (same as Table 1, item 2 but 0 type is excluded).
2. The next eight bits contain the region number of the nonordinary region.
3. The next 14 bits contain the location relative to Table 3 where the region data are listed.

#### Table 3

This table contains the parameters that define each region. The first location is referenced from Table 1 or Table 2.

##### 1. Ordinary Parallelepipeds

The first six entries contain the six bounding planes ( $x_i^\alpha, x_i^\beta, i = 1, 2, 3$ ). The next six entries contain the adjacent region numbers for each of the corresponding six sides.

- a. If a side sees more than one region this side is defined as a complex surface. The entry contains the negative of the location relative to Table 3 where the data for the complex surface may be found. At this location relative to Table 3 the following information is recorded:
  - (1) A word containing the number of horizontal and the number of vertical intervals for the complex surface packed 18 bits apart.
  - (2) Following this word appear the upper limit of each of the horizontal intervals.

- (3) Then the upper limits of each of the vertical intervals appear.
- (4) Finally, packed four to a word, nine bits apart, are the regions on the complex surface. The region numbers along the horizontal, from the first to the last horizontal interval are listed for the first vertical interval; then for the second vertical interval, etc. as shown in Fig. 6.
- b. If the side sees only one region then the region number of this region appears.

## 2. Nonordinary Regions (Types 1-5)

### a. Spheres

The first three entries contain the coordinates of the center of the sphere. The next entry is the square of the sphere radius.

### b. Cylinders

The first three entries contain the coordinates of the center of the base. The next entry contains the square of the base radius. The next three entries contain the x-y-z components of the height vector of the cylinder.

### c. Nonordinary Parallelepipeds

The first three entries contain the coordinates of the vertex of the parallelepiped. The next nine entries contain the x-y-z components of the three vectors which define the parallelepiped.

### c. Wedges

The description for the wedge is the same as the nonordinary parallelepiped, the two first vectors defining the legs of the wedge right triangle.

### e. Right Frusta of Cones

The first three entries contain the coordinates of the center of the lower base. The next two entries contain the square of the radii of the

lower and upper bases respectively. The following three entries contain the x-y-z components of the height vector.

### 6.3.3 Input Sheets for EZGEOM

Input sheets for EZGEOM are shown on the following pages.

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# EZGEOM INPUT

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**Repeat above 2 cards for each cylinder**

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\*See Section 6.1

**Repeat above 3 cards for each wedge**

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**Repeat above 3 cards for each non-ordinary rectangular parallelepiped**

Page 7 of 7

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## 7. THE TRACING AND SCORING MONTE CARLO PROGRAM – ADONIS

Having appropriate output tapes of DATORG, VANGEN or GASP, and EZGEOM, we are ready to proceed with the transport game<sup>7</sup> for the solution of the Boltzmann integral equations. The transport game is basically an analog of the physical transport of a neutron or a gamma ray. However, in most problems, it is necessary to modify the game to obtain the desired result efficiently.

At each event to be considered in the game, a weight is introduced. The purpose of carrying along the weight is to enable the consideration of altered games of chance which lead to appreciable variance reductions. At the present time, the ADONIS program employs two methods of variance reduction: importance sampling, and statistical estimations in the special case of flux evaluation in small detector regions.

As the transport game is played, a variety of information, including the following, is recorded.

1. The average flux as a function of energy group in each ordinary and non-ordinary region along with its standard deviation. If any quantity proportional to the flux is desired, it can be computed using appropriate response functions.
2. A neutron interaction tape for future secondary source emission processing .

3. A tape containing information on transmitted particles for future processing.
4. The number of absorptions per element and per region, births and deaths due to importance sampling in each region, and energy degradations below an optional energy cutoff.
5. The average flux as a function of energy at specified detector points along with its standard deviation (optional, for neutron problems only).

We turn our attention to the description of the transport game played by ADONIS.

### 7.1 THE TRACKING PROCESS

The ADONIS program uses the source particle tape created by VANGEN, GASP, or a similar source generator program to start particle histories. The position,  $\underline{P}$ , the energy,  $E$ , and the direction,  $\underline{\Omega}$ , of the source particle, and  $R_i$ , the region in which the particle is born, are read off the tape.

The first problem that must be solved is to determine the position of the next collision and the region in which that collision will occur. It can be shown that the number of mean free paths,  $\lambda$ , that a neutron is to travel before interacting must be selected from a probability distribution function  $e^{-\lambda}$  (using the definition of the transport kernel in the Boltzmann integral equation). Then, the distance from  $\underline{P}$  along  $\underline{\Omega}$  to the first collision location  $\underline{P}'$  is given by

$$\lambda - \sum_{k=i}^{\eta} \mu_T(E, R_k) S_k = 0 \quad (55)$$

where  $\mu_T(E, R_k)$  = the total cross section at energy  $E$  of the composition in region  $R_k$

$S_k$  = the distance along the particle flight path in region  $R_k$ .

$R_i, R_{i+1}, \dots, R_k, \dots, R_{\eta}$  are the regions which are seen successively along the flight path.

Further, it can be shown that, if  $\xi$  is a random number in the interval (0, 1), the probability distribution for  $-\ln \xi$  is  $e^{-\lambda}$ .

Therefore,

$$\lambda = -\ln \xi \quad (56)$$

The techniques used by the ADONIS program to solve the problem now can be discussed.

1. A random number,  $\xi$ , is selected using the subroutine RANDM. This subroutine is written in FORTRAN language and generates equi-distributed pseudorandom numbers on the interval (0, 1) compatible with the word length of the computing machine used. For the CDC-1604-A, the period of the random number sequence is  $X_0 = 5^{13}$  and the starting number is usually an odd prime number. The successor,  $\xi_{n+1}$ , of a random number,  $\xi_n$ , is obtained by taking the product  $X_0 \xi_n$ , rejecting the first half of the significant figures of the product and floating the remainder.
2. The number of mean free paths  $\lambda$  is computed using Eq. 56.
3. The cross section  $\mu_T(E, R_i)$  of the composition in the region where the particle is born is computed by linear interpolation of the cross sections generated by DATORG at the output energies defined in the GENDA routine. The subroutine Data Retrieval, entry 1 (DR,1) computes the interpolation factor,  $f$ . The subroutine Data Retrieval, entry 2 (DR,2) computes  $\mu_T(E, R_i)$  using the interpolation factor obtained from (DR,1) and the table of total cross sections for the composition in  $R_i$ . Note that in going through regions containing different compositions without change in particle energy, only (DR,2) is called since the interpolation factor is unchanged.
4. Given the location  $\underline{P}$  and the direction  $\underline{\Omega}$  in a given region,  $R_i$ , the subroutine Geometry 1 (G1) determines how far it is to the next region and

what surface the particle will cross if it does travel that far, using the geometry tables created by EZGEOM (Section 6) and special routines for each type of region, G1 (TYP), where TYP = ORP, SPH, CYL, WED, RPP. These denote ordinary region, sphere, cylinder, wedge, or non-ordinary parallelepiped, respectively.

The number of regions,  $m_B$ , wholly contained in a given region  $R_i$  is obtained from Table 1.

If  $m_B = 0$ , G1(TYP) and  $R_i$  determine  $S_i$ . The intersection  $\underline{P}'$  of the flight path with the appropriate edge of  $R_i$  is computed\* and

$$S_i = |\underline{P}' - \underline{P}|.$$

If  $m_B \neq 0$ , G1 determines whether or not the flight path intersects each of the  $m_B$  regions enumerated in Table 2 using G1(TYP). If there is no intersection with any of these regions, the procedure is similar to the case  $m_B = 0$ . If there are one or more intersections, the distances from  $P$  to the intersection points are computed and the shortest distance is then retained.

5. The next task is to determine whether or not the particle makes a collision before traveling the distance  $S_i$ .

If  $\lambda - \mu_T(E, R_i) S_i > 0$ , the particle does cross into the next region. A subroutine called Geometry 2 (G2) is now used to determine the region,  $R_{i+1}$ , and the particle enters using the information gathered in Tables 2, 3, and G1. Then the remaining number of mean free paths is determined by replacing  $\lambda$  by

$$\lambda' = \lambda - \mu_T(E, R_i) S_i \tag{57}$$

and the procedure is repeated by computing  $\mu_T(E, R_{i+1})$  and going to G1. In other

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\*The method used in these computations has been described in unpublished memos by J. Certainé.<sup>8,9,10</sup>

words, the particle is tracked into the next region. There are, however, two important tests that are performed before tracking in the next region is started. First, the program determines whether the region in which the particle enters is a reflecting or transmitting region. \*

If this is the case, the tracking of the particle is terminated and the proper reflecting or transmitting counters are updated.

If the region is neither reflecting nor transmitting, a second test is performed. As pointed out above, the consideration of variance reduction techniques may lead to the introduction of weighting functions which are position and energy dependent.

At the present time, ADONIS considers weighting functions piecewise constant in each region and in given energy intervals,  $W(E, R)$  (Section 7.3.1). The program compares the ratio of weights at energy  $E$  in region  $R_i$  and  $R_{i+1}$ .

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\*It is necessary to terminate the particle tracking upon leaving the environment of the geometrical configuration of interest. Three devices have been built into the program to handle this situation.

1. If the "importance" of a particle in a particular region is made sufficiently low, the particle entering that region will be killed (see Section 7.3).
2. If a fictitious macroscopic absorption cross section sufficiently large is attached to a given region, incident particles will be absorbed.
3. A very rapid way to terminate particle tracking is accomplished by the introduction of two special types of regions: the reflecting region (required to be region 1) and the transmitting region (which can be any region) which have the following properties:
  - a. Particles incident on both regions are terminated and counted separately.
  - b. For transmitted particles only, the location at which the particle path flight enters the region, the energy, the direction, and the original history number of the particle and the region from which the particle has come are recorded on a tape in the same order as specified for the source tape (Section 5).

$$\frac{W(E, R_i)}{W(E, R_{i+1})} = N + F \quad (58)$$

where  $N$  and  $F$  are the integral and fractional portions of the quotient, respectively.

A random number  $\xi$  is selected and compared to  $F$ ; then, if  $\xi < F$ ,  $N$  is replaced by  $N+1$ . If  $\xi > F$ ,  $N$  is left unchanged.  $N$  is by definition the number of particles created. If  $N = 0$ , the tracking is terminated and the counter registering the number of deaths by importance sampling is increased by 1. If  $N = 1$ , no additional particle has been created and the tracking of the particle is continued. Note that if  $W(E, R) = 1$  for all  $E$  and  $R$ , this means that the transport game is modeled directly after the physical problem of particle transport. If  $N > 1$ , the phase-space coordinates of the  $N-1$  additional particles are put into a table along with the number  $N-1$ . This entry in the table is defined as  $(N-1)$  latent particles. The tracking is continued with the  $N^{\text{th}}$  particle. When tracking of a particle is terminated, the program searches the latent table, picks the last latent particle entered and starts tracking it. The particle history is terminated when tracking of the original particle and all the latent particles is completed.

The region in which the particle makes a collision is determined as follows. Starting from region  $R_i$ , the above procedure is continued until it is found that in some region  $R_k$

$$\lambda - \mu_T(E, R_k) S_k < 0 \quad (59)$$

The program then proceeds to bring the particle to the collision point in  $R_k$ . Indeed, the distance from the edge of region  $R_k$  to the collision point is given by  $\lambda/\mu_T(E, R_k)$ .

We must now determine with which element in the region  $R_k$  the particle collides, the type of collision, and the energy and direction of the emerging particle, if

any. This is obtained by the interaction routines which are described in Section 7.2.

The tracking of the particle coming out of collision is resumed by choosing a new  $\lambda$  and repeating the process described above.

## 7.2 THE INTERACTION ROUTINES

The interaction experienced by the particle is determined in two steps. First the interacting element is chosen; second, the specific event is chosen. If the event is scattering, the energy and direction of the scattered particle are evaluated.

The interacting element is chosen by comparing the product of a random number with the total macroscopic cross section of the region composition,  $\xi \mu_T(E, R)$ , with the total macroscopic cross section of each element in that composition,  $\mu_T(E, e_j)$ , where  $e_j$  denotes the  $j^{\text{th}}$  element in the composition of region  $R$ ,  $j = 1, 2, \dots, \ell, \dots, L$ . If

$$\sum_{j=1}^{\ell-1} \mu_T(E, e_j) < \xi \mu_T(E, R) < \sum_{j=1}^{\ell} \mu_T(E, e_j), \quad (60)$$

then the interacting element is  $e_{\ell}$ .

The type of interaction is similarly determined by comparing a random number to the probabilities that a given event takes place. These probabilities have been tabulated for each element by the GENPRO routine.

The ADONIS subroutine which is used to select the interacting element and the type of interaction is called Data Retrieval, entry 3 (DR,3).

The incident energy,  $E$ , is referenced with respect to the output mesh energies  $E_j^G$  in an energy interval  $(E_j^G, E_{j+1}^G)$  by (DR,1). For each element, at each  $E_j^G$ ,

GENPRO supplies tables of total microscopic cross sections, scattering probabilities, absorption probabilities, and a scattering index. This index gives the type of scattering, if any, e.g., elastic, discrete or continuum inelastic. If elastic scattering is indexed, it gives the type of elastic scattering that the particle suffers. For anisotropic elastic scattering, discrete inelastic, or continuum inelastic scattering, the scattering index gives the proper location of the tables of probabilities supplied by GENPRO: CHI, PLEV, and ENN tables (see Section 3).

(DR,3) compares a random number,  $\xi$ , in (0,1) to the probability of scattering at energy E [obtained by interpolation using the  $f$  computed by (DR,1)].

If the event is absorption, the number of absorptions in the element and the region are updated, the particle tracking is terminated, and tracking of a latent particle, if any, is started.

If the event is scattering, the energy after scattering, EPRIM, ( $E'$ ), and the cosine of the angle of scattering in the laboratory system, CSTHT, ( $\cos \theta$ ), are computed by calling the appropriate routines: ELAS and INELAS for neutron elastic and inelastic scattering, respectively, and NIKI for gamma elastic scattering.

### ELAS Routine

The control digit NCBD is set to 1, 2, 3, 4 for the following cases: (1) isotropic in center of mass system, (2) hydrogen scatterer, (3) anisotropic scattering, and (4) isotropic in laboratory system – no energy degradation.

#### 1. Isotropic Scattering in Center of Mass System

It can be shown that if  $\xi$  is random in (0,1)

$$X = \frac{1 - \cos \theta_c}{2} = \xi \quad (61)$$

where  $\theta_c$  is the scattering angle in the center of mass system.  $E'$  and



$\cos \theta$  are then obtained by the standard relations

$$E' = E \left[ 1 - \frac{4AX}{(1+A)^2} \right] \quad (62)$$

$$\cos \theta = \frac{A+1-2AX}{(A+1) \left[ 1 - \frac{4AX}{(A+1)^2} \right]^{1/2}} \quad (63)$$

where  $A$  = the element atomic weight

$E$  = the incident energy.

## 2. Hydrogen Scatterer

Upon collision with hydrogen, particles are scattered in the forward direction only. It can be shown that the probability distribution function  $\cos \theta$  is given by  $2 \cos \theta$ .

To pick a  $\cos \theta$  from the distribution  $2 \cos \theta$ , two random numbers<sup>11</sup> are selected and the larger of the two is retained as  $\cos \theta$ . Then

$$E' = E (\cos \theta)^2 \quad (64)$$

## 3. Anisotropic Scattering

The cosines of angles between which elastic scattering is equally probable for the specified energy mesh points,  $E_j^G$ , are supplied in the CHI tables referenced by the scattering index.

If the incident neutron energy,  $E$ , lies in the interval  $(E_j^G, E_{j+1}^G)$ , the CHI table relative to  $E_j^G$  is selected. This tabulation consists of

$$\chi_n = \frac{1 - \cos \theta_n}{2} \quad \text{for } n = 0, 1, 2, \dots, N$$

where  $\chi_0 = 0$ ,  $\chi_N = 1$ ,  $0 \leq \chi_n < 1$ .

In ADONIS,  $N$  is restricted to 10. The proper  $\chi$  is selected by choosing a random number,  $\xi$ , and comparing the product  $10\xi$  to the numbers 1, 2, ...,  $N = 10$  successively.

Assume that  $n < 10\xi < n+1$

This means that  $\chi_n < \chi < \chi_{n+1}$

The integral part of the product  $10\xi$  is rejected and the remainder is taken as the interpolation factor,  $f$ . [This assumes a uniform probability distribution of  $\chi$  in each interval  $(\chi_n, \chi_{n+1})$ .]

Then

$$\chi = \chi_n + f(\chi_{n+1} - \chi_n) \quad (65)$$

This function is performed by the Data Retrieval, entry 6 routine (DR,6).

Therefore,

$$\cos \theta = 1 - 2\chi \quad (66)$$

and  $E'$  is obtained using Eq. 62.

#### 4. Isotropic in Laboratory System – No Degradation

If the scatterer atomic weight is large, Eqs. 62 and 63 show that

$$E' \approx E \quad (67)$$

$$\cos \theta \approx 1 - 2\chi = \cos \theta_c \quad (68)$$

Thus, the scattering is approximately isotropic in the laboratory system and the particle energy remains unchanged by the collision. Therefore, a random number,  $\xi$ , is chosen and  $\cos \theta = 1 - 2\xi$ .

### INELAS Routine

Data Retrieval, entries 7 and 8 subroutines, (DR,7) and (DR,8) are entered for discrete and continuum scattering, respectively (overlapping is included in the continuum spectrum), to select  $E'$ .

If  $E$  lies in  $(E_j^G, E_{j+1}^G)$ , the PLEV and ELEV tables\* for discrete scattering or the ENN table\* for continuum scattering relative to  $E_j^G$  are selected.

To select from the ENN table, (DR,8) uses the same technique as (DR,6).

To select from the PLEV table, (DR,7) uses the same technique as (DR,3) in the selection of the interacting element.

Using the inequality (Expression 60) in which the element  $e_j$  is replaced by the energy levels, one obtains the appropriate energy level  $E'$  to which the particle scatters and  $E' = E - E''$ .

### The NIKI Routine

It is assumed that  $\gamma$ -scattering results from the Compton effect. A  $\gamma$ -ray of energy  $\alpha$  (in  $mc^2$ ) traversing matter has a probability,  $p(\chi/\alpha) d\chi d\ell$ , of having a collision in the distance  $d\ell$  and emerging from this collision with an energy  $\alpha' = \chi\alpha$ . For  $\chi$  satisfying  $1 \leq \chi \leq 1 + 2\alpha$ ,

$$p(\chi/\alpha) d\chi = \frac{A}{\chi^2} (\cos^2 \theta - 1 + \chi + \frac{1}{\chi}) d\chi, \quad (69)$$

where  $A = n\pi\alpha_0^2/\alpha$

$n$  = the number of electrons per  $cm^2$

$\alpha_0$  = the classical radius of the electron

$\theta$  = the scattering angle which is related to  $\alpha$  and  $\chi$  by the Compton relation

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\*See Section 3.

$$\cos \theta = \frac{1}{\alpha} - \frac{\chi}{\alpha} + 1. \quad (70)$$

$p(\chi/\alpha)$  is called the Klein-Nishina probability distribution function. To pick a  $\chi$  from  $p(\chi/\alpha)$ , a rejection technique devised by H. Kahn is used in ADONIS.<sup>11</sup>

$p(\chi/\alpha)$  is broken up into the sum of two probability distribution functions. A random number,  $\xi_1$ , is compared to  $(2\alpha+1)/(2\alpha+9)$ .

If  $\xi_1 < (2\alpha+1)/(2\alpha+9)$ ,  $y$  is set equal to  $1 + 2\alpha\xi_2$  (where  $\xi_2$  is a second random number), and another random number,  $\xi_3$ , is compared to  $4 [(1/y) - (1/y^2)] = m$ .

If it is less than  $m$ ,  $\chi = y$ . If it is greater than  $m$ ,  $y$  is rejected and the procedure is repeated.

If  $\xi_1 > (2\alpha+1)/(2\alpha+9)$ ,  $y$  is set equal to  $(2\alpha+1)/(1+2\alpha\xi_2)$ , and  $\xi_3$  is compared to

$$\frac{1}{2} \left( \cos^2 \theta + \frac{1}{y} \right),$$

where

$$\cos \theta = \frac{1}{\alpha} - \frac{y}{\alpha} + 1.$$

If it is less than  $(1/2) [\cos^2 \theta + (1/y)]$ ,  $\chi = y$ . If it is greater than  $(1/2) [\cos^2 \theta + (1/y)]$ ,  $y$  is rejected and the procedure is repeated.

Once  $\chi$  has been selected, NIKI proceeds to compute  $E'$  and  $\cos \theta$ .

The interaction routines compute and transmit to the main program the energy after scattering,  $E'$ , and the cosine of the scattering angle,  $\cos \theta$ . What is required is to evaluate the direction cosines of the new particle direction in the Cartesian coordinate system, given  $\cos \theta$  and the initial direction cosines. The DIREC routine computes these angle cosines by means of two subroutines:

1. Subroutine PHI uses a rejection technique to choose the cosine and sine of an azimuthal angle equidistributed in the interval  $0 \leq \phi \leq 2\pi$ :  $\cos \phi$  and  $\sin \phi$ .
2. Subroutine DCB computes the direction cosines

$$\underline{\Omega}' = (\Omega'_x, \Omega'_y, \Omega'_z) :$$

$$\Omega'_x = \sqrt{\frac{1-\mu^2}{1-\Omega_z^2}} (\Omega_y \cos \phi + \Omega_z \Omega_x \sin \phi) + \Omega_x \mu$$

$$\Omega'_y = \sqrt{\frac{1-\mu^2}{1-\Omega_z^2}} (\Omega_y \Omega_z \sin \phi - \Omega_x \cos \phi) + \Omega_y \mu$$

$$\Omega'_z = \sqrt{(1-\mu^2)(1-\Omega_z^2)} \sin \phi + \Omega_z \mu \quad (71)$$

where  $\mu = \cos \theta$ ;

$\underline{\Omega} = (\Omega_x, \Omega_y, \Omega_z)$  is the given initial direction.

### 7.3 VARIANCE REDUCTION TECHNIQUES

As pointed out in the introduction to this section, the transport game is altered for better efficiency. In shielding problems, one is interested in particles from a source which are transmitted through the shield. In problems of interest, the transmission is generally small, and, if results with reasonable accuracy are required, an extremely large number of particle histories must be considered. This involves large amounts of computing time; thus it is costly.

To obtain a practical calculation, one must do other than play the direct analog game in which a great deal of time is spent on particles which are not transmitted. Many methods have been tried in which the situation is improved by computing the same average scores but with a reduced variance. Most of these increase the work per game, but hopefully result in a net saving of work. The method of reducing variance in the main program of ADONIS is a particular case of

importance sampling. However, for the special problem of evaluating neutron fluxes in a small volume detector, a different approach is used. Here, instead of decreasing the variance by altering the game, the variance is decreased by changing the method of scoring.<sup>12-15</sup> This method is called statistical estimations, or scoring by analytical estimations.

### 7.3.1 ADONIS Importance Sampling

In altering the direct analog game of chance to reduce variance, one tries to estimate the desired result by emphasizing the choice of phase space points which lead to higher expected contribution to the score.  $I(\underline{x}, E, \underline{\Omega})$  is a measure of the "importance" of the point  $(\underline{x}, E, \underline{\Omega})$ .

It can be shown that<sup>7</sup> the use of  $I(\underline{x}, E, \underline{\Omega})$  leads to a game in which particles are picked from an altered source,  $\tilde{S}(\underline{x}, E, \underline{\Omega})$ , and collision locations and energy and direction of scattered particles are chosen from an altered kernel,  $\tilde{K}(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}')$  such that

$$\tilde{S}(\underline{x}, E, \underline{\Omega}) = \frac{I(\underline{x}, E, \underline{\Omega}) \cdot S(\underline{x}, E, \underline{\Omega})}{\int I(\underline{x}, E, \underline{\Omega}) S(\underline{x}, E, \underline{\Omega}) d\underline{x} dE d\underline{\Omega}} \quad (72)$$

and

$$\tilde{K}(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}') = \frac{I(\underline{x}, E, \underline{\Omega})}{I(\underline{x}', E, \underline{\Omega}')} K(\underline{x} \rightarrow \underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}') \quad (73)$$

where  $S$  and  $K$  are the normalized source and the collision kernel, respectively, of the integral Boltzmann equation.

The questions are how to choose the most efficient importance function,  $I$ , and, having chosen  $I$ , how do we play the game of chance?

A proper choice of  $I$  forces particles to points in phase space such that their contribution to the desired answer will be large. As a matter of fact, there exists

an ideal importance function which leads to a zero variance game. It can be shown that the most efficient important functions are solutions to the adjoint equations to the Boltzmann equation.<sup>12-15</sup> Obtaining these solutions presents an equally difficult problem. In practice, the choice of  $I$  is limited because it depends on the complexity of the kernel,  $\tilde{K}$ . The Boltzmann equation kernel,  $K$ , is itself the product of the transport kernel,  $T(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega})$ , and the collision kernel,  $C(\underline{x}'; E \rightarrow E'; \underline{\Omega} \rightarrow \underline{\Omega}')$ . Hence, we could attach an importance function to each of these kernels separately. The "importance" of a particle will then be governed by the importance of the region in the phase space in which it finds itself at the moment. In ADONIS, the importance function is taken as a piecewise constant function of energy and space and independent of direction angle, i.e.,  $I(E, \underline{x}) =$  constant in each region  $R_i$  and each energy interval,  $E_j^G < E < E_{j+1}^G$ .

Consider now a particle at energy  $E$  leaving collision at  $\underline{x}$  in region  $R_i$ . When the particle goes from  $\underline{x}$  to  $\underline{x}'$ , the collision density is changed by the ratio of the importance function at the new point to the importance function at the old point,  $[I(E, \underline{x}')]/[I(E, \underline{x})]$ . To insure the correct collision density at the new point, we may follow the particle from  $\underline{x}$  to  $\underline{x}'$  using  $T(\underline{x} \rightarrow \underline{x}'; E)$ . Having reached the new collision point, create the number  $[I(E, \underline{x}')]/[I(E, \underline{x})]$  to go into collision at  $\underline{x}'$ . This method assures us of always having the correct collision density since

$$\tilde{T}(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega}) = \frac{I(E, \underline{x}')}{I(E, \underline{x})} T(\underline{x} \rightarrow \underline{x}'; E, \underline{\Omega}) \quad (74)$$

In ADONIS, a slightly different method is used by considering the region boundaries at which the importance function changes. Suppose that the particle starting from  $\underline{x}$  in  $R_i$  crosses the boundary between regions  $R_i$  and  $R_{i+1}$  and that

$$\frac{I(E, R_{i+1})}{I(E, R_i)} = 2.$$

Then the collision density is supposed to double. One way of insuring this is by

creating another particle, precisely like the first, and then following both. Of course, when the particle crosses the boundary from  $R_{i+1}$  to  $R_i$ , we have to halve it. One way of halving a particle is by "killing" it half the time. The first process is called "particle splitting" and the second process is referred to as "Russian roulette."

Similarly, when the particle enters collision at  $\underline{x}'$ , say in region  $R_k$ , the "splitting" or the "Russian roulette" technique is used according to the magnitude of the ratio  $I(E', R_k)/I(E, R_k)$ . We could make the importance function resemble even more closely the true function by including an angular dependence. However, it is no small task to assign, even for simple geometries, an importance function as a function of  $\underline{x}$ ,  $E$ , and  $\Omega$  in each region.

Note that a weighting function is used in ADONIS. The weight is merely the inverse of the importance, i.e.,

$$W(E, R) = \frac{1}{I(E, R)} \quad (75)$$

When a particle goes from a point  $[E, \underline{x}(R_i)]$  to a point  $[E', \underline{x}(R_j)]$ , we create or kill

$$\frac{W[E, \underline{x}(R_i)]}{W[E', \underline{x}(R_j)]} = \frac{I[E', \underline{x}(R_j)]}{I[E, \underline{x}(R_i)]} \quad (76)$$

particles. The technique used in ADONIS to create or kill particles has been described in Section 7.1.

We now investigate techniques whereby one can get relatively good importance functions.

For the situation in which the importance function is dependent on position only,  $I(R)$ , it has been shown that it should have the property of keeping the particle flux about constant from one region to the next. What is done in practice is to



run a problem with relatively few histories and see whether the condition is satisfied. If it is not, then we alter the boundaries according to the following criterion. Whenever the number of particles falls off too rapidly, one introduces additional importance boundaries, or increases the value of the importance functions and keeps the boundaries intact. The reverse is done whenever the number of particles increases too rapidly. Some trial and error along with educated guessing can often lead to a good importance function.

When the importance function depends upon energy as well, the same method is used by recording the number of particles created in each energy group for each spatial region.

### 7.3.2 Scoring by Analytical Estimations – Flux at a Point<sup>16</sup>

In some neutron calculations, it is desirable to obtain answers for flux, dose, or the like at a point. Since no history can be expected to carry a neutron through a point, it is necessary to use analytic expected value estimates. The method uses the relation between  $\psi(\underline{x}', E, \underline{\Omega}) d\underline{x}' dE d\underline{\Omega}$ , the density of particles entering collision in volume  $d\underline{x}'$  with energy in  $dE$  and direction in  $d\underline{\Omega}$ , and  $\phi(\underline{x})$ , the flux at  $\underline{x}$ .

$$\phi(\underline{x}) = \int dE' \int d\underline{x}' \int dE \int d\underline{\Omega} \psi(\underline{x}', E, \underline{\Omega}) \times \left\{ 2g \left( \frac{\underline{x} - \underline{x}'}{|\underline{x} - \underline{x}'|} \cdot \underline{\Omega}, E \right) \left[ \frac{e^{-\mu(E') |\underline{x} - \underline{x}'|}}{4\pi |\underline{x} - \underline{x}'|^2} \right] \right\} \quad (77)$$

where  $g(w; E) dw$  = the probability of scattering of a neutron of energy  $E$  through an angle whose cosine is in the range  $(w, w+dw)$

$E'$  = the energy after scattering

$\mu(E')$  = the total attenuation coefficient of the scattered neutron.

The problem is to evaluate the estimator in brackets in Eq. 77 every time a particle goes into collision and average it over all histories. A straightforward procedure yields an infinite variance if  $|x-x'|$  can become very small. Indeed, the estimator has a  $|x-x'|^{-2}$  behavior. The method devised by Kalos and employed in ADONIS to avoid infinite variances is to remove the singularity from the scoring function and to incorporate it in the sampling probability distribution function (pdf).

What is required is that for every collision, we estimate the "once-more collided" contribution to the flux at a point and choose the position of the intermediate collision to make the variance finite. Hence, the final estimate is the collided flux only. A separate analytic calculation must be made for the uncollided flux.

If S, D, and A denote the collision point, the detector, and the intermediate point, respectively, and  $R = |\underline{SD}|$ ,  $r_1 = |\underline{SA}|$ , and  $r_2 = |\underline{AD}|$ , the following pdf is selected:

$$U_2 dV = \frac{\mu'}{8\pi} \left[ \frac{e^{-\mu' r_1}}{r_1^2} + \frac{e^{-\mu' r_2}}{r_2^2} \right] dV \quad (78)$$

where

$$\mu' = \mu(E) + \frac{1}{R} \quad (79)$$

Noting that  $U_2$  is an average of two pdf's, each of the form

$$\frac{\mu'}{4\pi} \frac{e^{-\mu' r}}{r^2}$$

where the origin of  $r$  is taken either at the collision point or the detector point, it is easy to sample from  $U_2$ .

1. Choose with equal probability either S or D
2. Choose the direction toward A isotropically
3. Choose a distance  $r$  from the pdf  $\mu' e^{-\mu' r}$ .

This distance is either  $r_1$  or  $r_2$  and the remaining distance must be computed. (Note that the direction toward the intermediate point A is chosen from an isotropic distribution. Thus, if the source particle angular distribution is not isotropic, the first direction picked from S must satisfy this distribution. At the present time, ADONIS assumes isotropic angular distribution of the source particles when the flux at a point routine is used.)

The contribution to the "once more collided flux at a given detector D" from a neutron of energy  $E$  and direction  $\underline{\Omega}$  entering collision at S is then given by

$$\begin{aligned} \phi(E_2, D) = & \{ [P(E, S)] g(\underline{\Omega} \rightarrow \underline{\Omega}_1; E) e^{-\sum_1 \mu(E_1, R_i) S_i} \\ & [P(E_1, A)] \mu_T[E_1, R(A)] g(\underline{\Omega}_1 \rightarrow \underline{\Omega}_2; E_1) e^{-\sum_j \mu(E_2, R_j) S_j} \} \\ & / U_2 (4\pi r_1^2) (4\pi r_2^2) \end{aligned} \quad (80)$$

where  $\underline{\Omega}_1, E_1$  = the direction and energy after scattering at S

$\underline{\Omega}_2, E_2$  = the direction and energy after scattering at A.

$$\sum_1 S_i = r_1$$

where  $S_i, i = 1, 2, \dots$ , denote the track lengths in the regions that the particle traverses from S to A.

$$\sum_j S_j = r_2$$

where  $S_j$ ,  $j = 1, 2, \dots$ , denote the track lengths in regions between A and D.  $U_2$  is computed using Eq. 78.

$[P(E, S)]$  means that a game of chance is played to find the interacting element and the type of interaction.

If the interaction at S or A is an absorption, the contribution to the once more collided flux at D is zero. If it is scattering, Eq. 80 is computed.

The contribution to the uncollided flux is finally added to obtain the total flux at detector D in each output energy interval.

$$\phi_{un}(E_2^j, D) = \frac{e^{-\sum_k \mu(E_2, R_k) S_k}}{4\pi R^2} \quad (81)$$

where

$$\sum_k S_k = R$$

where  $S_k$ ,  $k = 1, 2, \dots$ , denote the track lengths in the regions between S and D, and  $E_2^j$  means that  $E_2$  is in the  $j^{\text{th}}$  output energy interval.

#### 7.4 TYPES OF ANSWERS

The ADONIS output consists of:

1. The average flux per region and per unit energy in each output energy interval, and its deviation
2. The volume V, the weight  $W(E, R)$ , the number of births (latent particles), deaths (by importance sampling), energy degradations (particles whose energy falls below a specified cutoff energy, if any) and absorptions in each region except the transmitting and reflecting regions
3. The number of transmitted and reflected particles

4. As an option, a total fine response and its deviations
5. As an option, coarse responses for any region
6. An interaction tape for neutron problems only
7. A transmitted particle tape.

Items 2, 3, 6, 7 have been discussed in the above subsections. This description will be restricted to items 1, 4, and 5.

#### 7.4.1 Average Flux

There are two ways to measure the average flux,  $\bar{\phi}$ , in a region. The usual way is to count  $m(R)$ , the number of interactions in the region, and if  $N$  is the number of source particles,

$$\bar{\phi} = \frac{m(R)}{\mu_T(R) N} \quad (82)$$

This method is inefficient when  $R$  is a thin region. It is then necessary to use the other method which is called the track length method:

$$\bar{\phi} = \frac{\text{Total distance all particles traveled in } R}{(\text{Volume of } R) \times N} \quad (83)$$

It can be shown that both methods are equivalent. ADONIS computes average flux per region and per unit energy in each output energy interval using the track length method.

The source particles are considered in  $G$  equal groups of  $n$  particles each, such that  $N = Gn$ , each group being denoted by  $g = 1, 2, \dots, G$ . For most cases, 20 particles per group are taken. In any case,  $n$  must be specified in the input. This grouping is made for statistical purposes. As it will be shown, although the contribution to the average flux of all track lengths is cumulative, the contribution to the variance depends strongly on the grouping.

Let  $S_g(R, E^j)$  be the sum of all track lengths of particles from the  $g^{\text{th}}$  group in region R with energy E in the  $j^{\text{th}}$  output energy interval.

The average track length per source particle per unit energy in the  $j^{\text{th}}$  interval is given by

$$\bar{S}(R, E^j) = \frac{\sum_{g=1}^G S_g(R, E^j)}{(E_j - E_{j+1}) \times G_n} \quad (84)$$

where  $E_j, E_{j+1}$  define the  $j^{\text{th}}$  energy interval.

The average flux per source particle per unit energy in the  $j^{\text{th}}$  interval in region R is given by

$$\bar{\phi}(R, E^j) = \frac{\bar{S}(R, E^j) W(E^j, R)}{V(R)} \quad (85)$$

where  $V(R)$  and  $W(E^j, R)$  are the volume and the weight in the  $j^{\text{th}}$  energy group of region R, respectively. If the energies are given in ev, track lengths in cm, and  $V(R)$  in  $\text{cm}^3$ ,  $\bar{\phi}(E^j, R)$  is obtained in number of particles per  $\text{ev-cm}^2$ -source particle.

If  $V(R)$  is infinite, the ADONIS output is the product  $\bar{S}(R, E^j) W(E^j, R)$ .

The deviation of the average flux is obtained from

$$\sigma(R, E^j) = \frac{\bar{\phi}(E^j, G) \cdot G}{\sum_{g=1}^G S_g(R, E^j)} \left\langle \frac{1}{G-1} \left\{ \frac{\sum_{g=1}^G S_g^2(R, E^j)}{G} - \left[ \frac{\sum_{g=1}^G S_g(R, E^j)}{G} \right]^2 \right\} \right\rangle^{1/2} \quad (86)$$

### 7.4.2 Fine Response

If a functional of the type

$$\bar{f}(R) = \int_R \int_E \phi(E, \underline{X}) f(\underline{X}, E) d\underline{X} dE \quad (87)$$

is desired (fine dose, heating ...), the ADONIS input contains a table of  $f(R, E_j^G)$  at the energies,  $E_j^G$ , of the cross section used in ADONIS (81 energy mesh points). Because of core storage restrictions, a maximum of five possible distinct regions can be considered for fine response evaluation [ $5 \times 81$  words for  $f(R, E)$  are available].

Each particle track length,  $T(R, E)$ , is multiplied by an interpolated value of the tabulated fine response function,  $f(R, E)$ , and the products are accumulated. Then the total fine response,  $\bar{f}(R)$  is given by

$$\bar{f}(R) = \frac{W(R)}{G \cdot n \cdot V(R)} \sum_{g=1}^G T(R, E) f(R, E) \quad (88)$$

The deviation of the fine response is given by

$$\sigma_{\bar{f}} = \frac{W(R)}{n \cdot V(R)} \left\langle \frac{1}{G-1} \left\{ \frac{\sum_{g=1}^G T(R, E) f(R, E)}{G} - \left[ \frac{\sum_{g=1}^G T(R, E) f(R, E)}{G} \right]^2 \right\} \right\rangle^{1/2} \quad (89)$$

Note that at the present time, a fine response calculation can be performed only if the region weight is not energy dependent.

### 7.4.3 Coarse Response

In any region,  $\bar{f}$  can be obtained by giving as input tables of  $f(E_j^j, R)$ , where  $f(E_j^j, R)$  is piecewise constant in each output energy interval. The coarse re-

sponse is then given by

$$\bar{f} = \sum_{j=1}^{J-1} \bar{\phi}(R, E_j) f(E_j, R) (E_j - E_{j+1}) \quad (90)$$

## 7.5 INTERMEDIATE RESULTS

For debugging purposes and other reasons, a trace using sense switch 3 has been built into the ADONIS code. This trace permits one to follow the flight of a given number of particles. When the number of specified source particles is exhausted, the program calls the edit routine STAT.

ADONIS problems may run for long periods of time. In order to save problems so that they may be restarted, the parameters used by ADONIS have all been stored in COMMON, so that if COMMON were written on a tape, read back, and the program entered at the proper place, one could continue a problem. This coding has been placed in the ADONIS code and is activated by sense switch 1 whose function is to dump COMMON and continue the problem (the computer will print a message telling the operator to turn off sense switch 1 and will hang waiting till he does). Sense switch 1 and sense switch 6 set together will dump a problem, force an edit, and terminate. To pick up a problem that has been dumped, one places a 1 in the restart option of the first parameter card and resubmits the job as a normal ADONIS run. The code reads the dump tape and picks up from where it left off. The first parameter card must be exactly the same as the initial parameter card with the following two exceptions: (1) the last history number may be increased and (2) the restart option must be a 1. The title and the first card are all the input necessary for restarting a problem. If coarse response function data are present, these must follow the first parameter card.



## 7.6 ADONIS INPUT

The input required for ADONIS consists of source input, cross-section input, geometry input, and parameter input describing the particular problem of interest.

### Source Input

The source input consists of a source tape containing source particles generated by programs like VANGEN or GASP. These source particles are arranged by particles blocked in groups of 100; each particle is represented by its history number, its initial position, direction, and energy, and the region of birth.

### Cross-Section Input

The cross-section input consists of the desired cross sections arranged in tables so that they are accessible to the ADONIS interaction routines. These tables are placed in the COMMON portion of memory by the program DATORG. This COMMON is consistent with that used by the ADONIS interaction routines. A variable storage design has been employed so that only that storage necessary for a given problem is reserved, leaving the remaining storage available for use where necessary so that the originator may be able to expand the input where desired.

### Geometry Input

Tables 1, 2, 3 described in EZGEOM are transmitted to ADONIS via COMMON.

### Problem Dependent Parameter Input

The program MPINP reads in cards describing the problem.

The first parameter card contains the limits of the problem as shown below.

Entry	Type of Limit
1	The number of the first history to be treated (usually 1)
2	The number of the last history to be treated

Entry	Type of Limit
3	The number of flux bins for flux tracking
4	The number of particles per group for statistical scoring of flux
5	The total number of ordinary and nonordinary regions in the problem
6	The transmitting region number
7	The total number of distinct weights, Q
8	The number of distinct region dependent weights, q
9	The number of distinct compositions (given as input to the associated DATORG problem)
10	The number of flux-at-a-point detectors ( $\leq 15$ ), if any
11	The number of fine response functions ( $< 6$ )
12	Restart option: 0 = original problem 1 = restart
13	The type of problem to be run: 0 = neutron 1 = gamma

Cards following the first parameter card contain the items listed below.

1. The cutoff energy and the thermal energy, if any. If the thermal energy entry is zero, particles slowing down below the energy cutoff are terminated and counted as degraded particles. If the thermal energy entry is nonzero, particles with energy below the energy cutoff are not terminated. They are assumed to be at thermal energy and no longer lose energy upon scattering. The cross sections used are the thermal cross sections. Absorption, reflection, transmission, or death by importance are then the only ways a history may be terminated.
2. The energy mesh points which define the output energy intervals follow. The number of entries corresponds to the number of specified energy bins plus one. The entries are in ev and in descending order.
3. The next input entries are the atomic weights per composition. This input consists of the atomic weights for each element of each specified composition, one composition per card. These cards are arranged in the

order corresponding to the DATORG input. This input is used as a check on the cross-section input read from the DATORG output. When a particle collides and the interacting element is determined, the mass of the element is taken from this list.

4. Next the weight numbers which are assigned to each region appear. Region-dependent weights and/or sets of region- and energy-dependent weights must be assigned to each region in the problem, as shown in Fig. 7. (If no importance sampling is desired, 1.0 is assigned as the weight for all regions.) For each distinct region-dependent weight and/or set of energy- and region-dependent weights, a unique number is assigned as follows: first, the numbers 1 to  $q$ , where  $q$  is the number of distinct region-dependent weights, are assigned to each of these weights; then the numbers  $q+1$  to  $Q$ , where  $Q$  is the total number of distinct weights, are assigned to each of the sets of energy- and region-dependent weights. This procedure is shown on the table in Fig. 7.

The first set of cards lists, in the order of the region number (14 to a card), the weight number assigned to each region, as shown in Fig. 7.

In the next set of cards the  $q$  region weights are entered in the order that the weight numbers were assigned. Then the  $Q-q$  sets of energy-dependent weights are entered, each set starting a new card and in the order of their weight numbers (Fig. 7).

5. The composition number per region input follows. The input consists of the composition number from one to the number of different compositions in the problem being assigned to each region. (This is the same procedure as that described for the weight numbers.)
6. The next type of input is optional. The number of fine response functions has been specified in the first parameter card. Each response function contains a title card, a card denoting the region to which this response

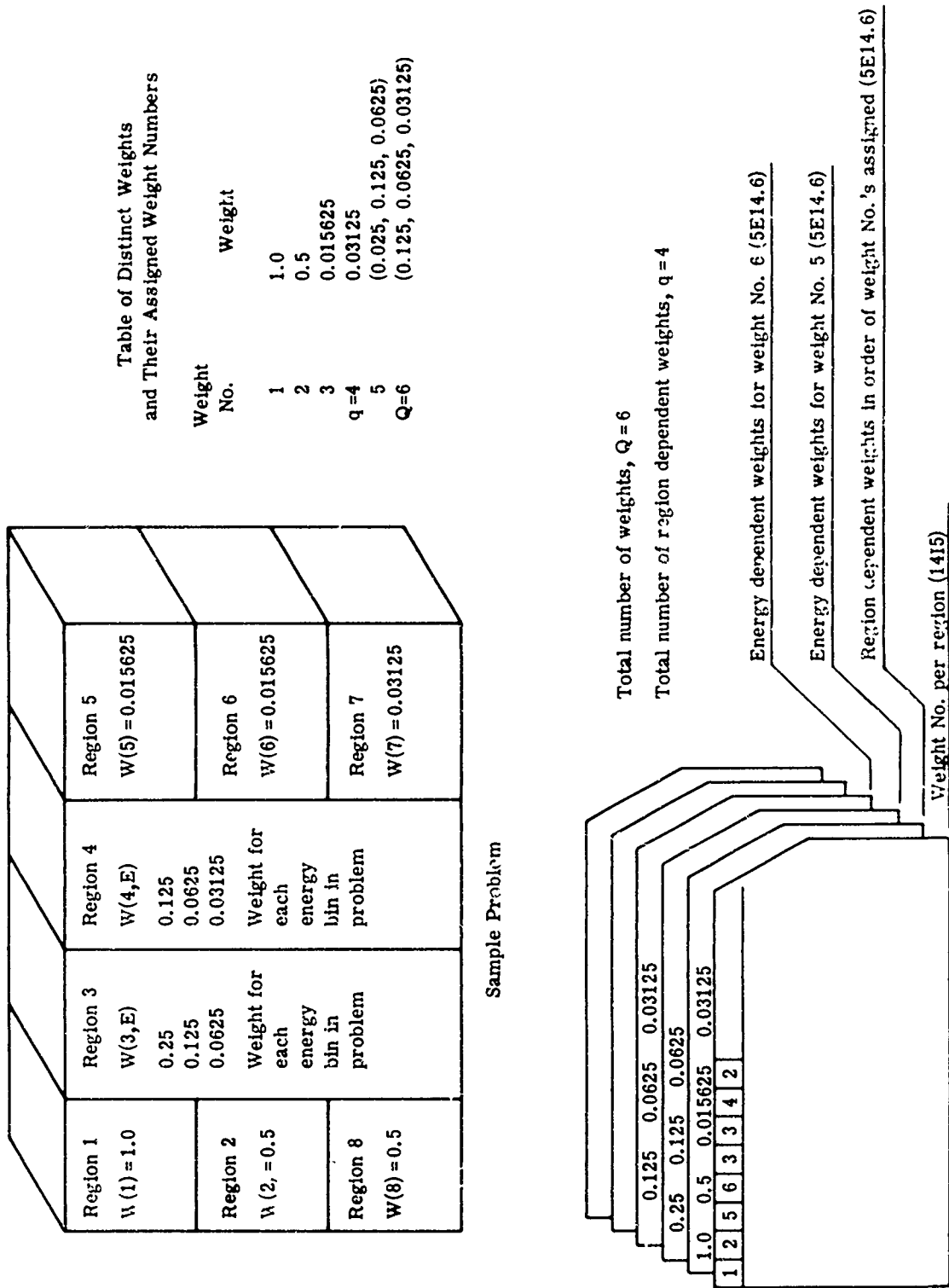


Fig. 7 — Sample input cards and problem

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function applies, and the response function enumerated at each of the mesh point energies,  $E_j^G$ , that were used to create the cross-section tape.

7. The following input for flux at a point is optional. This input consists of a card containing the number of output energy bins plus one. The limits of the energy intervals are listed in ev and in descending order. A title card is next. Following the title card are cards containing the x-y-z coordinates of the detector points and the regions in which the detectors are located. The number of these cards corresponds to the number of detectors specified.
8. Finally, the coarse response function input appears. This input consists of:
  - a. A card denoting the number of coarse response functions desired  
(0 means no coarse response is desired)
  - b. Each response function is described in the following cards.
    - (1) A title card
    - (2) A region information card containing the number of regions for which this coarse response function applies
    - (3) The average response function for each output energy interval
    - (4) A table of the regions to which this response function applies.

## 7.7 ADONIS INPUT FORMS

ADONIS input forms are shown on the following pages.

[illegible]

TITLE CARD		Card I.D. No.
Print option 0=double space, then print 1=print on new page	ANY KIND OF TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)	
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>		73 174 175 176 177 178 179 180
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>		G, P - 12 10 0 1

PROBLEM INFORMATION CARD										Card I.D. No.		
Initial history number (usually 1) (to change the random number sequence, make this number one greater than a multi- ple of the number of histories per group)	Final history number	Number of histories per statis- tical group	Number of energy bins for track length computa- tions	Total number of regions	Region number to which particles escape	Total number of distinct composi- tions ( $\leq 20$ )	Total number of distinct weights dependent of energy dependent weights counts as one)	Number of region dependent weights	Number of detectors for flux at a point calculation		Number of fine response functions ( $< 6$ )	Restart option 0=no restart 1=restart
0 1 9 1 10	15 116 117 118 119 120	23 24 25	26 27 28 29 30	31 32 33 34 35	36 37 38 39 40	41 42 43 44 45	46 47 48 49 50	51 52 53 54 55	56 57 58 59 60	61 62 63 64 65	66 67 68 69 70	71 72
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>												73 174 175 176 177 178 179 180
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>												G, P - 12 10 0 2

ENERGY INFORMATION CARD		Card I.D. No.
( cutoff energy, eV	Thermal energy cutoff: if this entry is zero, then the cutoff energy is the energy below which particles are counted as degra- dations. If this entry is nonzero, then the cutoff energy is the energy below which particles assume the smallest energy of the cross sections used, and this energy contains the thermal cross sections. (Particles do not degrade.)	
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>	<div style="border: 1px solid black; height: 15px; width: 100%;"></div>	73 174 175 176 177 178 179 180
<div style="border: 1px solid black; height: 15px; width: 100%;"></div>	<div style="border: 1px solid black; height: 15px; width: 100%;"></div>	G, P - 12 10 0 3



[illegible][illegible]

\*N<sup>o</sup>. sequentially

ADONIS GROUP-2 INPUT (CONTINUED)

Page 4 of 12

WEIGHT NUMBER PER REGION CARDS												ENTER WEIGHT NO. CORRESPONDING TO EACH REGION. (REGIONS ARE IN ASCENDING ORDER.) WEIGHT NUMBERS SHOULD BE IN ACCORD WITH FOLLOWING WEIGHTS.												Card I.D. No																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340	1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373	1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384	1385	1386	1387	1388	1389	1390	1391	1392	1393	1394	1395	1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439	1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	1454	1455	1456	1457	1458	

(See Fig. 7, second card)

START A NEW CARD FOR EACH SET OF ENERGY DEPENDENT WEIGHTS. EACH ENERGY CORRESPONDS TO THE ENERGY BINS FOR THE TRACK LENGTH CALCULATION.

[illegible]

(See Fig. 7, third and fourth cards)

# ADONIS GROUP-2 INPUT (CONTINUED)

Page 7 of 12

COMPOSITION CARDS		ENTER COMPOSITION NO. CORRESPONDING TO EACH REGION. (REGIONS ARE IN ASCENDING ORDER.) COMPOSITION NUMBERS SHOULD BE IN ACCORD WITH DATORG INPUT.																												Card I.D. No.
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	73 174 175 176 177 178 179 180
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	C1O1M4P1 0 0 1
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	C1O1M4P1 0 0 2
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	C1O1M4P1 0 0 3
5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	C1O1M4P1 0 0 4
6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	C1O1M4P1 0 0 5
7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	C1O1M4P1 0 0 6

(See Section 7.6)

FILL O FOR EACH (-5) REGION FOR WHICH A FINE RESPONSE FUNCTION IS REQUIRED

TITLE ALPHABETICS AND NUMERICS ACCEPTABLE										Card I.D. No.†
1	2	3	4	5	6	7	8	9	0	1
10	11	12	13	14	15	16	17	18	19	2
20	21	22	23	24	25	26	27	28	29	3
30	31	32	33	34	35	36	37	38	39	4
40	41	42	43	44	45	46	47	48	49	5
50	51	52	53	54	55	56	57	58	59	6
60	61	62	63	64	65	66	67	68	69	7
70	71	72	73	74	75	76	77	78	79	8
80	81	82	83	84	85	86	87	88	89	9
90	91	92	93	94	95	96	97	98	99	0
*Pt option: 0 double space 1 new page										FIRFI

FINE RESPONSE FUNCTION INFORMATION CARD										Card I.D. No.†
Function for which Response Function is to be calculated					Number of energies (as per cross-section data tape)					
1	2	3	4	5	6	7	8	9	0	1
10	11	12	13	14	15	16	17	18	19	2
20	21	22	23	24	25	26	27	28	29	3
30	31	32	33	34	35	36	37	38	39	4
40	41	42	43	44	45	46	47	48	49	5
50	51	52	53	54	55	56	57	58	59	6
60	61	62	63	64	65	66	67	68	69	7
70	71	72	73	74	75	76	77	78	79	8
80	81	82	83	84	85	86	87	88	89	9
90	91	92	93	94	95	96	97	98	99	0
										FIRFI

FINE RESPONSE FUNCTION CARDS (14 CARDS FOR 81 ENERGIES)										Card I.D. No.†
Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Response Function†	Card I.D. No.†
1	2	3	4	5	6	7	8	9	0	1
10	11	12	13	14	15	16	17	18	19	2
20	21	22	23	24	25	26	27	28	29	3
30	31	32	33	34	35	36	37	38	39	4
40	41	42	43	44	45	46	47	48	49	5
50	51	52	53	54	55	56	57	58	59	6
60	61	62	63	64	65	66	67	68	69	7
70	71	72	73	74	75	76	77	78	79	8
80	81	82	83	84	85	86	87	88	89	9
90	91	92	93	94	95	96	97	98	99	0
										FIRFI
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TITLE CARD FOR DETECTORS		ANY KIND OF TITLE OR PROBLEM IDENTIFICATION (CAN BE BOTH ALPHABETIC AND NUMERIC)	Card I.D. No.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80			
			D E F T E C

DETECTOR CARDS (AS MANY AS NECESSARY)				Region No. where detector is located	Card I.D. No.
X coordinate of detector	Y coordinate of detector	Z coordinate of detector			
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80					
•	•	•			0 0 1
•	•	•			0 0 1 2
•	•	•			0 0 3
•	•	•			0 0 4
•	•	•			0 0 5
•	•	•			0 0 6
•	•	•			0 0 7
•	•	•			0 0 8
•	•	•			0 0 9
•	•	•			0 1 0
•	•	•			0 1 1
•	•	•			0 1 2
•	•	•			0 1 3
•	•	•			0 1 4
•	•	•			0 1 5
•	•	•			0 1 6



COARSE RESPONSE FUNCTION INFORMATION CARD		Card ID No
Number of coarse response functions to follow*		
1		73174172176177178179180
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\*If there are no coarse response functions, but external response functions are required, enter 0 in column 10.

REPEAT EACH OF THE FOLLOWING FOR EACH COARSE RESPONSE FUNCTION

[illegible]

\*Print control option: 0 = double space  
1 = new page

REGION INFORMATION CARD		Card I D No t
Number of regions for this response function		
1	1	23
2	2	24
3	3	25
4	4	26
5	5	27
6	6	28
7	7	29
8	8	30
9	9	31
10	10	32
11	11	33
12	12	34
13	13	35
14	14	36
15	15	37
16	16	38
17	17	39
18	18	40
19	19	41
20	20	42
21	21	43
22	22	44
23	23	45
24	24	46
25	25	47
26	26	48
27	27	49
28	28	50
29	29	51
30	30	52
31	31	53
32	32	54
33	33	55
34	34	56
35	35	57
36	36	58
37	37	59
38	38	60
39	39	61
40	40	62
41	41	63
42	42	64
43	43	65
44	44	66
45	45	67
46	46	68
47	47	69
48	48	70
49	49	71
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72	72	94
73	73	95
74	74	96
75	75	97
76	76	98
77	77	99
78	78	100

[illegible]

**Number sequentially**

**Note:**

These cards must be in direct correspondence with energy bin cards in this section.

[illegible]

\*Reg. numbers for coarse response function  
†Number sequentially

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## 8. DESCRIPTION OF THE UNC-SAM PROGRAM SEQUENCER (SAM)

UNC-SAM contains a program sequencer (SAM) whose functions are listed below.

1. To read the program name card which appears in the input. For example, in Fig. 8, it will read first the DATORG card.
2. To check that programs that supply input have been run. In the case of DATORG, it will check that the output of GENPRO is available.
3. To read in and execute the appropriate program.
4. Upon completion of the program to check that no error has occurred. In the event of an error, UNC-SAM will bypass all subsequent programs which require the output of this program.
5. To read the next program name card and to repeat the procedure from item 2.

When SAM reads an "END" as a program name card, the program sequence is terminated. SAM is the main program on an overlay tape (logical tape 3) containing the DATORG, EZGEOM, VANGEN, GASP, and ADONIS programs.

Input\* required for SAM are the numbers 0, 1, or 2 corresponding to each of the programs on the overlay tape.

0 means the corresponding program will not be run in this sequence.

1 means the corresponding program will be run.

---

\*The description of the proper program input appears in the input section.

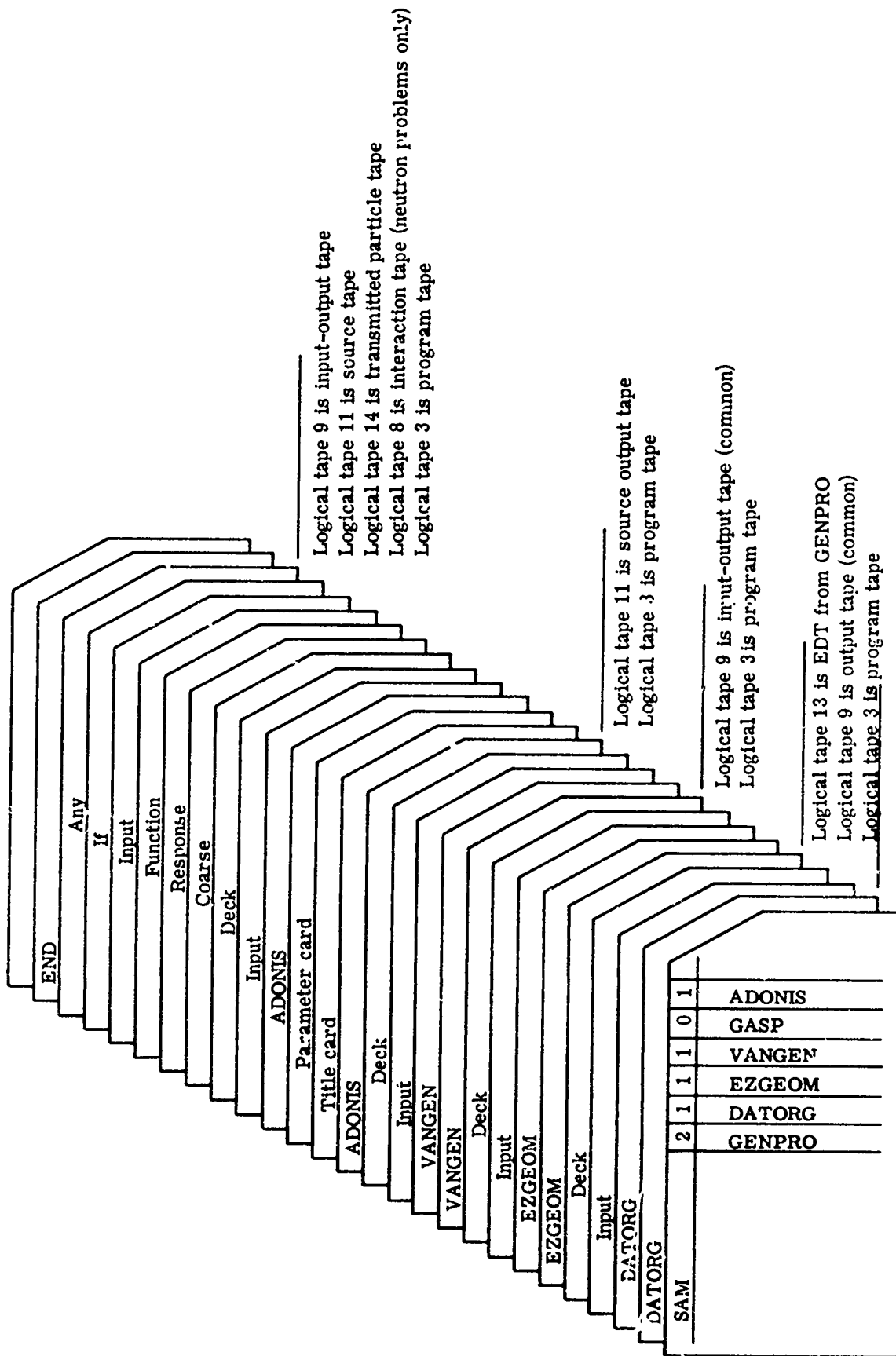


Fig. 8 — Input sequence and tape assignment for running DATORG, EZGEOM, VANGEN, and ADONIS

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2 means the corresponding program has been run, and that the output is available for a program that will be run in this sequence.

The GENDA and GENPRO programs that supply the Element Data Tapes (i.e., the cross-section library) are separate. The Element Data Tape (output from GENPRO) is required to run DATORG. Consequently, the numbers 0 or 2 only apply as an entry in the SAM input for the program GENPRO.

A program in the sequence may appear in any order, provided all the programs that supply input to it have previously been run.

The input required for each program is preceded by a program name card.

The storage has been arranged so that all data that are problem-dependent, or are necessary for restarting a problem from a previous dump, appear in the COMMON portion of core. With this arrangement one can dump only the COMMON portion of the core on tape and be able to restart an ADONIS problem (Fig. 9). The COMMON storage tape (logical 9) must be present at all times when UNC-SAM is being used.

The program DATORG requires as input a tape containing the library of cross sections (neutron or gamma depending upon the problem specified) and composition input cards.

To signify that the cross-section tape (logical tape 13) is available, a 2 is placed in the SAM input card corresponding to the GENPRO program. To signify that DATORG is to be run, a 1 is placed in the DATORG position of the SAM card. The cross-section output of a successfully completed DATORG problem is placed on the COMMON storage tape (logical tape 9).

The COMMON storage tape (logical tape 9) is required by the program EZGEOM so that the output of a successful run may be added (if DATORG has been run pre-

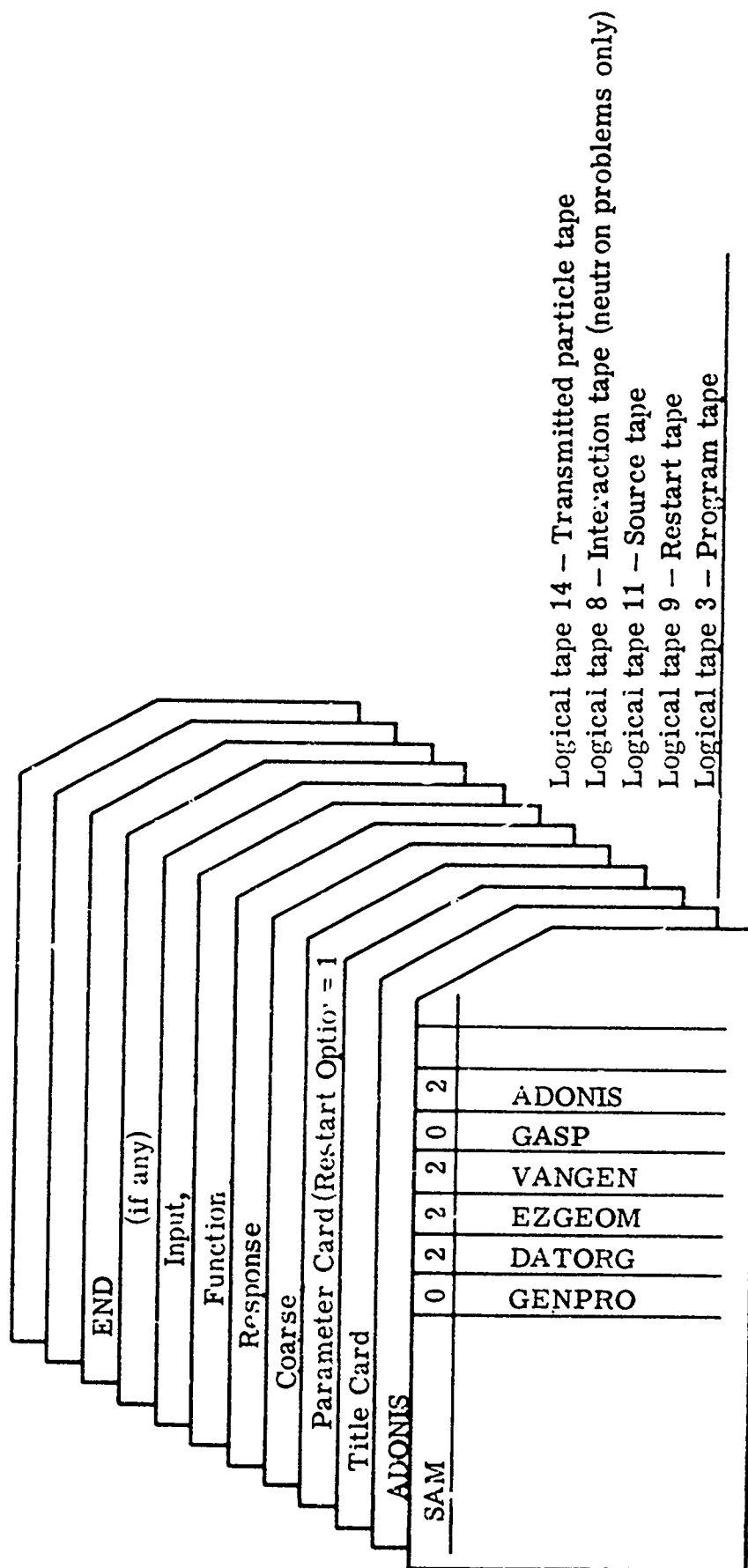


Fig. 9 — Job sequence and tape assignment for restarting an incompleted ADONIS problem



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viously), or initialized (if DATORG has not been run previously). Geometry card input data are also required to run EZGEOM (see Section 6).

The program VANGEN requires logical tape 11 as an output tape (source tape), and card input data (defining the source distribution) (see Section 5.6.1).

The program GASP requires that logical tape 11 be assigned as output and logical tape 8 from a previously run primary problem be assigned as input. Also, card input data are required (see Section 5.6.2).

The program ADONIS requires a source tape (logical tape 11) and the COMMON storage tape (logical tape 9) as input, a transmitted particle tape (logical tape 14) and an interaction tape (logical tape 8 for neutron problems only) as output.

Card input data are also required (see Section 7).

An array called TAB 3, dimensioned for 15,000 words, has been set aside to store the geometry, cross section, and statistical scoring arrays for each region (births, deaths, absorptions, degradations, sum of track-lengths for each energy bin in each region, the cumulative flux, and the cumulative square flux, the weights and composition numbers).

This array is arranged in the following manner:

Type of Data	Number of Computer Words Used
1. Geometry data	Problem dependent: (number, E, is printed when EZGEOM is run)
2. Cross-section data	Same as entry 1: D is printed (DATORG)
3. Output flux energy bin limits	J (number of energy bins) + 1
4. Weight numbers (for each region)	I (number of regions)
5. Region-dependent weights	NRDW (number of region-dependent weights)

Type of Data	Number of Computer Words Used
6. Energy-dependent weights	(IDWT-NRDW)J (IDWT = total number of distinct weights)
7. Composition per region	I
8. Absorption per region	I
9. Deaths per region	I
10. Degradations per region	I
11. Births per region	I
12. Absorption per element per region	5·I
13. Cumulative track-length in each region and energy group	J·I
14. Cumulative track-lengths	J·I
15. Cumulative square track-lengths	J·I

The use of variable dimensioning allows for an interplay of energy bins, regions, cross-section data, and total geometry data. As long as the total number of words does not exceed 15,000, one may run an ADONIS problem.

$$D + E + 11I + 3J \times I + J + 1 + \text{NRDW} + J(\text{IDWT} - \text{NRDW}) \leq 15,000$$

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# SAM CONTROL CARD

SAM TITLE CARD		0=NO GENPRO output necessary 2=GENPRO element data tape available for DATORG computa- tion		0=DATORG not to be run 1=DATORG to be run (column 25 must be 2) 2=DATORG has been run, the x-sec- tions generated are available on the restart tape	0=EZGEOM not to be run 1=EZGEOM to be run 2=EZGEOM has been run, the output is available on the restart tape	0=VANGEN not to be run 1=VANGEN to be run 2=VANGEN has been run, the output is available	0=GASP not to be run 1=GASP to be run 2=GASP has been run, the output is available	0=ADONIS not to be run 1=ADONIS to be run 2=ADONIS has been run, the output is available		Card I.D. No.
1	2	3	4	5	6	7	8	9	10	11
12	13	14	15	16	17	18	19	20	21	22
23	24	25	26	27	28	29	30	31	32	33
34	35	36	37	38	39	40	41	42	43	44
45	46	47	48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63	64	65	66
67	68	69	70	71	72	73	74	75	76	77
78	79	80	81	82	83	84	85	86	87	88
89	90	91	92	93	94	95	96	97	98	99
S A M										0 0 1

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